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# Investigating the amino acid digestibility of alternative protein sources and determining the impact of dietary fiber on energy, nitrogen, and amino acid digestibility in growing pigs

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# INVESTIGATING THE AMINO ACID DIGESTIBILITY OF ALTERNATIVE PROTEIN SOURCES AND DETERMINING THE IMPACT OF DIETARY FIBER ON ENERGY, NITROGEN, AND AMINO ACID DIGESTIBILITY IN GROWING PIGS

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# ABSTRACT

Cotten, Bradley M. M.S., Purdue University, May 2015. Investigating the amino acid digestibility of alternative protein sources and determining the impact of dietary fiber on energy, nitrogen, and amino acid digestibility in growing pigs. Major Professor: Olayiwola Adeola.

Three experiments were designed to quantify the nitrogen (N) and amino acid (AA) digestibility of various protein sources fed to growing pigs. The protein ingredients were sunflower meal, cottonseed meal, canola meal, camelina meal, egg albumen, casein, blood meal, plasma meal, potato protein concentrate, soy protein concentrate, soy protein isolate, and linseed meal, which were fed as the sole source of amino acids for the animals and were included in semi-purified, corn starch-based diets. A semi-purified, nitrogen-free diet (NFD) was used to estimate endogenous losses of AA. In each experiment, pigs were surgically fitted with a simple T-cannula at the distal ileum and fed four experimental diets and the NFD based on a 5 X 2 crossover arrangement in a randomized crossover design, with 5 diets and 2 periods. For experiment 1 (Exp. 1), sunflower meal, cottonseed meal, canola meal, and camelina meal were fed to 19, 42-kg barrows to determine the apparent (AID) and standardized (AID) digestibility of AA at the terminal ileum. The AID and SID of N and all AA were greatest for sunflower meal ($P < 0.05$), and canola meal had similar AID and SID of N, Met, Thr, Leu, and Val. The AID and SID of all essential AA, except for Met and Trp, was lower in camelina meal

than sunflower meal ($P < 0.05$). Cottonseed meal had lower AID and SID of Lys, Ile, Leu, Met, Thr, and Val compared to the other protein sources ($P < 0.05$). In experiment 2 (Exp. 2), egg albumen, casein, blood meal, and plasma meal were fed to 20, 20-kg barrows to determine the AID and SID of N and AA. The AID and SID of N and indispensable AA was greatest for casein compared to the other ingredients ($P < 0.05$). Blood meal, plasma meal, and egg albumen had similar AID and SID of many AA. Egg albumen had the greatest AID and SID of Cys among ingredients, while plasma meal had greater AID and SID of Thr than blood meal ($P < 0.05$). For experiment 3 (Exp. 3), potato concentrate, soy concentrate, soy isolate, and linseed meal were fed to 20, 25-kg barrows. The AID and SID of N was similar for potato concentrate, soy concentrate, and soy isolate and greater than linseed meal ($P < 0.05$). The AID and SID of Leu and Thr were greater in potato protein concentrate than soy concentrate ($P < 0.05$), and AID and SID of Thr was lower in soy isolate than potato concentrate. The apparent and standardized digestibility of all essential amino acids was similar between soy isolate and soy concentrate, and only the AID and SID of Asp was greater in soy isolate than soy concentrate ($P < 0.05$). Linseed meal had the lowest AID and SID of N and AA digestibility among protein sources ($P < 0.05$) in this experiment. In conclusion, animal protein and plant protein concentrates had the highest AID and SID of N and AA, and the digestibility of N and AA vary greatly among oilseed meals.

As more grain by-products and alternative feed ingredients are being fed to livestock, researchers are determining the impact that fibrous components have on nutrient digestibility. Two experiments were conducted to determine the impact that different types of fiber have on the energy, nitrogen (N), and amino acid (AA)

digestibility of soybean meal fed to growing pigs. In both studies, soybean meal served as the predominant form of amino acids for the animals, as the fibrous ingredients added little protein to the semi-purified, corn-starch based diets. A semi-purified, nitrogen-free diet (NFD) was used to estimate endogenous flows of AA. Pigs were surgically fitted with a simple T-cannula at the distal ileum and fed four experimental diets and the NFD on a 5 × 2 crossover arrangement in a randomized crossover design, with 5 diets and 2 periods. For experiment 1 (Exp. 1), soybean meal (SBM), SBM + corn hulls, SBM + rice hulls, and SBM + wheat straw were fed to 19, 45-kg barrows to determine apparent (AID) and standardized ileal digestibility (SID) of N and AA at the terminal ileum, apparent total tract digestibility (ATTD) of energy and N, and apparent hindgut digestibility (AHD) of energy and N. Rice hulls reduced the AID and SID of N, Arg, Ile, Thr, Trp, and Cys compared to the control and corn fiber diets and had lower AID of N and Glu and SID of N and Leu compared to the wheat straw diet ($P < 0.05$). Wheat straw decreased the AID of Thr and Val compared to the control diet ($P < 0.05$), but did not inhibit the SID of AA. The AID and SID of N and AA between the control and corn fiber diet were similar in the study. The inclusion of rice hulls reduced the AID of energy and N, the ATTD of energy, and the HAD of energy compared to the control group ($P < 0.05$). The AID, ATTD, and AHD of energy was lower in pigs fed wheat straw compared to the control diet ($P < 0.05$); however, wheat straw did not influence N digestibility. The AID, ATTD, and HAD of N and energy of corn fiber was similar to the control. For experiment 2 (Exp. 2), sugar beet pulp was fed at four different inclusion levels (0 g/kg, 100 g/kg, 200 g/kg, and 300 g/kg) in soybean meal, cornstarch-based diets to 20, 35-kg barrows. Sugar beet pulp inclusion reduced the AID

and SID of N and all indispensable and dispensable AA compared to the control diet (linear, $P < 0.05$). The AID of energy and N were significantly reduced with sugar beet pulp was fed (linear and quadratic, $P < 0.05$). Sugar beet pulp further reduced the ATTD of energy (linear and quadratic, $P < 0.05$) and N (linear, $P < 0.05$). There were no differences in AHD of energy and nitrogen among treatments. In conclusion, the SID and AID of N and AA and ATTD of energy and N is uniquely impacted by the source and inclusion level of fiber in diets fed to growing pigs.

# CHAPTER 1.
# LITERATURE REVIEW

## Alternative Feed Ingredients in Swine Production

Continual growth of the world's human population has resulted in competition for nutrient-dense grains between animal production and food and fuel industries (CAST, 1999). As animal production is increasing in congruence with the human population, the demand for premier nutrient sources, such as soybean meal, is rising, resulting in high costs and low supply of these ingredients for animal production (Goldsmith, 2008). Agriculture producers are actively searching for low-cost, alternative feed ingredients that supply adequate nutrients and energy to livestock. Therefore, this thesis was constructed to determine the bioavailability of alternative protein sources in swine diets. With many low-cost ingredients containing significant concentrations of fibrous components, the impact of various sources of fibrous feedstuffs on amino acid (AA) and energy digestibility in diets fed to pigs was also examined. Due to extensive microbial fermentation occurring in the large intestine of the gastrointestinal (GI) system, swine may be able to utilize the energy of high fiber by-products while maintaining appropriate nutrient absorption.

Soybean meal is a by-product of soybean (*Glycine max*) processing that is predominantly fed as a protein source to livestock. Soybeans naturally contain trypsin

inhibitors that can impede amino acid digestion. Crushing soybeans removes fat from the grain (to be used for human food and fuel industries) and heating the defatted grain reduces the activity of trypsin inhibitors, resulting in a protein-rich feed referred to as soybean meal (SBM). Being the world's most produced oil meal, SBM is rich in lysine, threonine, and tryptophan, which are often in low concentrations in common cereal grains (Oil World, 2011). An industry standard involves adding soy hulls back to dehulled SBM, to result in an ingredient consisting of 44% crude protein (CP). Researchers have observed improved amino acid digestibility of SBM when soy hull inclusion was reduced and SBM contained 48% CP (NRC 2012, Dilger et al., 2004). With soy hulls containing approximately 10% CP, it can be estimated that 44% CP SBM contains approximately 11% more soy hulls than 48% CP SBM. Soy hulls consist mainly of dietary fiber, and chemical analysis of the ingredient reveals that it contains approximately 36% crude fiber (CF), 59.39% neutral detergent fiber (NDF), 41.55 % acid detergent fiber (ADF), 75% total detergent fiber (TDF), 66% insoluble Fiber and 7.5% soluble Fiber (NRC, 2012; Burkhalter et al., 2001). SBM containing 44% CP has been analyzed to contain approximately 8% ADF, 13% NDF, and 19% TDF (Grieshop et al., 2003; NRC, 2012).

Sunflower meal is the fourth largest oilseed meal produced in the world and results from oil extraction of sunflower seeds (Oil World, 2011). Sunflower (*Helianthus annuus*) seeds provide a valuable source of oil for the human food industry, containing significant levels of linoleic acid. Solvent extraction of sunflower seeds is more efficient at removing fat than mechanical (crushing) extraction, and sunflower meal contains different levels of fat, CP, and energy depending on the extraction process.

Furthermore, sunflower meal can be partially dehulled to improve the CP and energy concentrations. Therein lies the potential to use sunflower meal as a protein supplement in livestock nutrition, and the processing of the ingredient greatly affects the nutritional value of sunflower meal. Researchers have found the amino acid digestibility of sunflower meal to be similar to SBM when fed to late growing-finishing pigs (Gonzalez-Vega and Stein, 2012). Used in experiments supporting this thesis, non-dehulled sunflower meal contains more dietary fiber than dehulled sunflower meal, which may impact nutrient digestibility. Non-dehulled sunflower meal contains approximately 31% CP, 23% CF, 37% NDF, 29% ADF, and 7.54% lignin (NRC, 2012).

After soybean meal, cottonseed meal is the most abundant plant protein source available in the United States. A byproduct of cotton (*Gossypium*), cottonseed meal contains significant levels of protein, dietary fiber, and gossypol. Gossypol is a naturally occurring phenol that inhibits intracellular dehydrogenase enzymes and can lead to erythrocyte cell death. When bound to lysine, gossypol remains undigested in the gastrointestinal tract and does not impact the health of the mammal. As cottonseed meal can be produced by expelling or solvent extraction of fat from cottonseeds, solvent extraction results in less fat and free-gossypol concentrations while increasing the protein content of the feed. Due to varying fiber and gossypol content, cottonseed meal may not be as readily digestible as other oilseed meals in swine diets (Gonzalez-Vega and Stein, 2012). According to the NRC (2012), expelled cottonseed meal contains approximately 40% CP, 14% CF, 5.5% ether extract, 25% NDF, and 18% ADF.

Being the second leading oilseed meal produced in the world, canola meal is a protein-rich by-product of canola seed production (Oil World, 2011). Canola was

developed from various lines of rapeseed (*Brassica napus* and *Brassica campestris/rapa*) to contain less erucic acid and less glucosinolates than rapeseed. Fat extracted from canola seeds provides a premium source of vegetable oil for human consumption, and the leftover meal offers a digestible source of protein and other nutrients for livestock. Canola meal nutrient composition is dependent upon the degree and nature of processing. Expelled canola meal undergoes mechanical extraction of fat, reducing the oil content from 40% in the seeds to approximately 20% in the meal. Solvent extracted canola meal is produced via uniform grinding of seeds and addition of hexane to separate the fat from the meal, resulting in less than 1% fat. Used in the current studies, solvent extracted canola meal is composed of 37% CP, 10% CF, 3.2% ether extract, 23% NDF, 15% ADF, 3.4% Lignin, and 26% TDF (NRC, 2012). Even though canola meal contains significant amounts of dietary fiber, nonruminants have been observed to readily digest the amino acids supplied by the feed (Newkirk et al., 2003).

Camelina (*Camelina sativa*) has gained increased popularity as an oil source for biofuel production due to its high fat content. After mechanical extraction of oil from the seeds, camelina meal contains high levels of protein, n-3 fatty acids, and glucosinolates. Glucosinolates are secondary plant metabolites that may impede animal production. Camelina meal has been observed to reduce diet palatability and decrease growth performance in broiler production (Ryhanen et al., 2007). However, research has also observed the amino acid digestibility of camelina meal to be comparable to that of canola meal when fed to growing pigs (Almeida et al., 2013). Camelina meal

contains approximately 35% CP, 12% CF, 19% ether extract, 25% NDF, and 14% ADF (NRC, 2012; Almeida et al., 2013).

Linseed (*Linum usitatissimum*), also known as flax, is unique among grains produced in the western countries due to its high content of omega-3 fatty acids. Due to the health benefits of omega-3 fatty acids in human health, the value and cost of linseed is relatively high compared to other grains, and its by-product, linseed (or flaxseed) meal is a potential protein source for livestock producers (Masood et al., 2005; Simopoulos, 1999). Like other oilseeds, the meal is either pressed or solvent-extracted from the original seed. With the lipid content of the meal being heavily dependent on the extraction method, linseed meal may contain up to 12% fat (Eastwood et al., 2009). By feeding high-fat linseed meal to swine, researchers have observed an increase in linolenic acid deposition in the carcass (Enser et al., 2000). Typically, linseed meal consists of 33% CP, 9.2% crude fiber, 6.5% ether extract, 25% NDF, 16% ADF, and 5.9% lignin (NRC, 2012).

Egg albumen (egg white) functions to provide protection and nutrition for developing embryos of poultry. As not all of the eggs produced by the layer industry are suitable for human consumption, researchers have investigated the use of egg byproducts in animal nutrition. Specifically, spray-dried egg albumen serves as an excellent source of amino acids and is produced after the shell and yolk are removed from unfertilized eggs. Comparable to the AA digestibility of spray-dried porcine plasma, egg albumen contains a high level of methionine, which may prove beneficial as many cereal grain-based diets are unable to supply enough methionine to satisfy livestock requirements (Owen et al., 1995). Egg albumen also contains lysozyme, an

antimicrobial protein that inhibits proliferation of gram-negative bacteria, which may further improve the performance and health of livestock (During et al., 1999). According to the NRC (2012), spray-dried egg albumen consists of approximately 51% CP and 34% ether extract.

Another animal-derived protein supplement, casein, is produced from pasteurized skim milk, which is a leftover material from cheese and butter production. Specifically, acidifying skim milk separates casein micelles from the liquid solution, which can then be dried and purified of caseinates (casein salts). Casein consists of phosphoproteins that form gels in gastric solution and provides highly digestible amino acids to mammals (Boirie et al., 1997). With the standardized ileal digestibility of nitrogen and many AA being greater than 95% in swine, casein is a highly digestible protein source that may be used to supplement nonruminants requiring nutrient-dense diets, such as weanling and finishing pigs (Cervantes-Pahm et al., 2010). This ingredient contains approximately 89% CP. 0.2% ether extract, and no detectable crude fiber (NRC, 2012).

For the past fifty years, blood meal, a byproduct collected at animal slaughterhouses, has served as a readily available protein source for animal producers. Containing high concentrations of amino acids, namely lysine, blood meal is used to supplement cereal grain-based diets fed to livestock. Spray drying blood meal at low temperature, followed by centrifugation and separation from foreign material, results in a highly digestible, intact protein. Both bovine and porcine-derived blood meals are currently used in swine diets. According to the NRC (2012), blood meal contains 89% CP, 1.5% ether extract, and no detectable crude fiber. Similar to blood meal, porcine

plasma meal, a byproduct of meat production, is produced by disallowing blood to coagulate, followed by centrifugation and extraction of the protein-containing liquid (plasma). Containing less protein than blood meal with similar AA digestibility, plasma meal contains approximately 78% CP, 2% ether extract, and no crude fiber (NRC, 2012). Spray-dried blood plasma has also been observed to improve the feed intake of nursery pigs compared to dried skim milk, soybean meal, dried whey protein, and spray-dried blood meal (Hansen et al., 1993).

Plant protein concentrates are rich sources of amino acids that provide an alternative to feeding animal-derived protein ingredients. Potato protein concentrate is produced by the extraction of starch from potatoes (*Solanum tubersum*). As potato protein generally contains significant levels of alkaloids that reduce feed intake, this ingredient is often thermally treated to remove the alkaloids while improving palatability and taste (Tusnio et al., 2007). As potato production and consumption continues to increase in developing countries, its protein concentrate may prove to be a valuable product in the global swine industry (FAO, 2008). Potato protein concentrate consists of 80% CP, 1.4% crude fiber, and 2.8% ether extract (NRC, 2012). While providing highly digestible amino acids, potato protein contains protease inhibitors that may impact the digestibility of this ingredient in livestock nutrition (Smith et al., 1996).

Other plant-derived protein concentrates that may be used in livestock nutrition include those extracted from soybeans, such as soybean protein concentrate and soy isolate. Defatted SBM contains water-soluble carbohydrates that are removed during ethanol extraction of SBM. With SBM fiber being mainly insoluble, the resulting product, soy protein concentrate, contains more of the original fiber than soy isolate.

According to the NRC (2012), soy concentrate contains 65% CP, 3.42% CF, 1.05% ether extract, 8.1% NDF, 4.4% ADF, and 19% TDF. Soy protein isolate is produced by separating and precipitating protein from soybean meal in aqueous solution, removing lipid and carbohydrate fractions from the final product (Cromwell, 2000). Soy protein isolate consists of 85% CP, 0.17% crude fiber, 2.8% ether extract, 0.19% NDF, and no detectable ADF (NRC, 2012). Both soy concentrate and isolate have been found to be readily digestible in diets fed to weanling pigs (Li et al., 1991).

Ethanol production is globally one of the fastest growing renewable energy industries, resulting in a great quantity of byproducts from corn (*Zea mays*) to be used in animal and human industries (Tolman and Tumbleson, 2006). The majority of ethanol is produced by the dry-milling process, in which corn kernels are hammered into a ground meal prior to fermentation to yield ethanol and Dried Distillers Grains (DDG). Corn can also be processed by wet-milling, which results in the separation of components to yield a variety of pure by-products. Following soaking of corn kernels in dilute sodium dioxide, corn germ can be extracted from the kernel and oil removed from the germ product. The resulting corn oil is often used in human food industries, and corn germ can serve as a feasible animal feed ingredient. After corn germ and oil extraction, the remaining kernel components contain significant amounts of protein, fiber, and starch. Corn gluten meal can be produced by adding dried steep liquor to the residual corn, resulting in a high protein ingredient. Aside from corn gluten meal, the corn residue can be further fractioned to separate fiber from the remaining protein and starch. This by-product is referred to as corn hulls, and little research has been conducted to determine the application of this ingredient in animal production. Corn

hulls consist of mainly insoluble fiber, with 15% cellulose, 35% hemicellulose, and 8% lignin fractions (Saha, 2003). Containing 10% crude protein, 70% NDF, and 17% ADF, corn fiber may provide an inexpensive source of protein and fermentable energy in swine production (de Godoy et al., 2009).

Rice (*Oryza sativa L.*) is commonly grown in national and international regions characterized by high moisture content in the soil. While the hull of rice contains high levels of fiber and silica, manufactures often dehull the grain to improve digestibility of rice products. After dehulling, the remaining components can be ground to produce rice bran, which has been shown to be fairly digestible when fed to swine (NRC, 2012). Containing mostly insoluble fiber with fractions of 38% cellulose, 18% hemicellulose, and 22% lignin, rice hulls can be used as litter for poultry, filler for pet foods, and as a carrier for vitamin/mineral premixes for animal agriculture (Salanti et al., 2010). To our knowledge, the impact of rice hull inclusion on the amino acid digestibility of diets fed to swine has never been investigated. As animal industries are continually searching for alternative sources of energy for diets, the ability of growing pigs to obtain energy from rice hulls by hindgut fermentation was also determined.

The stalks of cereal grains and legumes can be separated and retained during harvesting. Cereal grain stalks, or straw, have often been used to supply bedding to animals in outdoor facilities, and researchers have investigated the nutritional characteristics of this abundant source of fiber. While reducing the digestibility of protein and NDF when fed to growing pigs at 15% of the diet, wheat straw has been observed to improve the performance and litter size of sows (Falkowska et al., 2006; Veum et al., 2009). Though the improved sow performance may be attributed to

reduced weight gain and improved gastric filling by fiber, the energy of high cellulose ingredients, such as wheat straw, may be digested in hindgut fermentation in pigs. Consisting almost entirely of insoluble fiber, wheat straw's fibrous components contain 40% cellulose, 25% hemicellulose, and 15% lignin (del Rio et al., 2012). As the impact of wheat straw has not been thoroughly investigated, research observing the amino acid and energy digestibility of diets containing wheat straw was conducted.

Sugar beet pulp is a by-product of sugar beet (*Beta vulgaris*) production and is considered a potential feed ingredient in the animal industry. Sugar beets are finely shredded to extract sugar-rich juice from the plant, which can be later refined to sugar and beet molasses. The remaining components are then pressed and dried to increase the nutrient density and storage capacity of the ingredient, which is referred to as pulp. Unique to sugar beet pulp is its high soluble fiber content (Pieper et al., 2012). Feeding high-soluble fiber ingredients to animals with extensive colonic microbial populations, such as swine, may yield high energy digestibility of the feedstuff (von Heimendahl et al., 2010). Consisting of 9% CP, 45% NDF, and 24% ADF, sugar beet pulp may impact energy and nutrient absorption in a different manner than other fibrous ingredients in diets fed to growing pigs (NRC, 2012).

## Digestibility of Protein Sources

Biofuel and human food industries have increased the usage of starch and oil from grains, resulting in a significant supply of oilseed meals and other by-products to be used as feed ingredients for animal production. Globally, the four most produced

oilseed meals are soybean meal, canola meal, cottonseed meal, and sunflower meal (Oil World, 2011). Soybean meal is a relatively ideal protein source for swine diets as the AA profile is complementary to cereal grains and the standardized ileal AA digestibility nears 90% for many essential AA (Gonzalez-Vega and Stein, 2012). Removal of soy hulls, which contains high amounts of insoluble fiber, has been shown to increase total CP of the ingredient and improve AA digestibility when fed to pigs (Dilger et al., 2004; Burkhalter et al., 2001). Canola, sunflower, and cottonseed meal are cheaper protein sources than SBM and may be used in substitution of SBM in modern swine production. Unfortunately, the AA profile of these ingredients and AA digestibility are generally poorer than SBM when fed to pigs (Smith, 1986; Moon et al., 1994). The standardized ileal digestibility of AA for these ingredients has been shown to be close to 75% for many essential AA when fed to pigs, with AA from sunflower meal being most digested, cottonseed meal AA being least, and canola meal being intermediate (Gonzalez-Vega and Stein, 2012). Though not as common as other oilseed meals, camelina meal is being investigated by researchers to determine its application as a protein source in pig diets. Being a fairly novel ingredient to the swine industry, camelina meal appears to be a viable protein source, as the standardized ileal digestibility of many essential AA are 75% in pigs (Almeida et al., 2013). Containing a fair amount of fiber content, linseed meal is a prominent protein source in ruminant nutrition and may also be a possible protein ingredient in swine diets, especially to mature pigs in the grow-finish phase. The standardized ileal digestibility of AA in linseed meal is similar to that of canola meal, with many essential AA being 80% digestible in swine (NRC, 2012).

Along with oilseed meals, an alternative to feeding SBM to pigs is the inclusion of protein concentrates, both animal and plant-based, in modern swine diets. Common animal-derived protein concentrates that have been used in swine nutrition are blood meal, blood plasma, and casein. Not only being characterized by high concentrations of essential AA, these ingredients also provide highly digestible AA. The standardized ileal digestibility of essential AA for blood meal and blood plasma reaches 90% in swine, while that digestibility is 95% in casein (NRC, 2012). Another animal protein that may be used in swine diets is egg albumen (white). Little research has been conducted to determine the AA digestibility of egg albumen in pigs, though one study has found that the apparent AA digestibility of egg albumen to be close to that of blood plasma (about 85%) when fed to young pigs (Schmidt et al., 2003).

As the costs of animal proteins increase and regulations limit the use of animal proteins in specific animal species and countries, researchers are also searching for highly digestible, plant-derived protein ingredients to use in pig production. Plant protein concentrates that show promise for application in swine production are potato protein concentrate, soy protein concentrate, and soy protein isolate. As the production of these concentrates involves the removal of fiber and other anti-nutritive components, the resulting ingredients provide readily digestible AA, with standardized ileal digestibility for many AA being close to or greater than 90% (NRC, 2012).

As the amino acid digestibility of many feed ingredients have been discussed, it is important to note that several native components of feed ingredients affect nutrient digestibility. One major influence of amino acid digestibility, as seen with SBM and soy

hulls, is the fiber content of the feedstuff. Therefore, aspects of fiber characteristics are discussed in following sections of this thesis.

## Fiber Characterization and Analysis

### *Definition of Fiber*

Fiber can be defined as a heterogeneous compound of carbohydrates and lignin that are not digested in mammalian digestive tracts by enzymes of endogenous secretion (Trowell et al., 1976; Carpenter, 2003; IOM, 2006). As starch is a highly digestible polysaccharide, dietary fiber specifically refers to non-starch polysaccharides, or NSP (Trowell et al., 1976). As researchers observed that certain NSP can have physiological roles in human and animal health (Carpenter, 2003; Liu et al., 2010), a more accurate definition of fiber would separate NSP into functional fiber, non-functional fiber, and total fiber. According to the Institute of Medicine (IOM, 2006), functional fiber refers to isolated, non-digestible carbohydrates that induce physiological responses in mammals. Non-functional (dietary) fiber usually consists of non-digestible carbohydrates and lignin of plant origin. Total fiber is the sum of functional and dietary fiber of a given ingredient (IOM, 2006). Specific to animal agriculture, researchers have observed the unique impact that various fibrous feedstuffs may have on animal performance (Urriola et al., 2010). Therefore, further classification of dietary fiber has resulted in terms such as crude fiber, neutral detergent fiber, acid detergent fiber, and total dietary fiber (sum of insoluble and soluble fractions) to describe the dietary fiber content in ingredients.

*Analysis of Dietary Fiber*

Procedures to calculate the dietary fiber concentration in feed ingredients involve the digestion of non-fiber components and the measurement of undigested material. Digestion of feed components is accomplished through the use of chemicals (acids, bases, etc.) or enzymes (proteases, amylases, etc.), followed by quantification of undigested residues through gravimetric or chromatographic measures.

Weende Crude Fiber (CF) is one method of fiber characterization involving the use of chemical digestion and gravimetric measurement of the undigested material (Grieshop et al., 2001). In this method, samples are digested with 1.25% sulfuric acid and 1.25% sodium hydroxide (Cho et al., 1997). The undigested material is then weighed, representing the crude fiber content of the original sample. However, this method results in incomplete recovery of cellulose, hemicellulose, and lignin fractions, which limits the application of crude fiber content in nutrition (Grieshop et al., 2001). Aufrere and Michalet-Doreau (1988) showed a significant difference in fiber digestibility between two ingredients of similar CF content, which may be due to underestimating the digestibility of ingredients with highly digestible cell walls, as seen in sugar beet and citrus pulps.

The Van Soest method is another chemical-gravimetric procedure that separates undigested material into two classes, neutral detergent (NDF) and acid detergent fiber (ADF), by accounting for specific fractions of the cell wall (Aufrere and Michalet-Doreau, 1988). Even though this procedure provides more information on the physiological characteristics of fiber in a sample, it fails to recover soluble dietary fiber such as pectins, gums, and beta-glucans (Grieshop et al., 2001). This lack of recovery

may be less concerning for diets predominantly consisting of insoluble fiber, such as corn and dried distillers grains (DDGS), than diets containing sugar beet pulp and soybean hulls, which contains significant soluble fiber (Johnston et al., 2003).

Total dietary fiber (TDF) analysis involves mimicking the digestion that occurs in the small intestine of mammals by adding multiple enzymes, such as amylases and proteases, to a sample during digestion (AOAC, 2006). TDF is the sum of water-soluble and insoluble NSPs of a given feed ingredient, which may provide a better prediction method for determining fiber digestibility due to the unique impact that water-soluble fiber can have on digestive contents (Johnston et al., 2003). The soluble and insoluble fiber fractions are separated by an 80% ethanol solution (AOAC, 2006). There remains little information on insoluble and water-soluble fiber fractions of feedstuffs used in swine production.

*Chemical Properties of Fiber*

Functional and dietary fiber consists of non-starch oligosaccharides and polysaccharides, and the linkages connecting monosacchrides directly influence the molecule's chemical properties, such as solubility, water-binding capacity, and viscosity. With cellulose consisting of beta (1-4) linkages between glucose units, water is unable to penetrate the rigid, crystalline structure, and fibers containing significant cellulose concentration are thereby insoluble in aqueous solution (Oakenfull, 2001). Cellulose and lignin have relatively low water-binding capacity, resulting in reduced solubility and unaffected viscosity (Shelton and Lee, 2000). In contrast, soluble fibers, such as beta-glucan, consist of beta (1-3) linkages between monosacchrides which enable a less rigid structure of the fiber (Oakenfull, 2001). This increases the water-

binding capacity of the fiber, which can then form gels in solution and increase the viscosity of the solution (Dikeman and Fahey, 2006).

Along with the ability to bind to water, dietary fiber can interact with organic molecules and minerals through free carboxyl groups and uronic acids of the fiber (Oakenfull, 2001; Kritchevsky, 1988). Phytates and lignin are non-carbohydrate components of fibrous material that also have the ability to bind to minerals, with lignin being one of the strongest binding agents in fiber (Kritchevsky, 1988).

## Digestibility of Fiber

### *Fermentation of Dietary Fiber*

Mammalian enzymes of endogenous secretion are able to hydrolyze multiple linkages in carbohydrates, including alpha (1-4) linkages in starch and beta (1-2) linkages in sucrose (Tso and Crissinger, 2000). However, mammals do not produce enzymes that degrade linkages in dietary fiber, such as beta (1-6) linkages in cellulose and beta (1-3) linkages in beta-glucans, and dietary fiber is only hydrolyzed by bacterial enzymes during fermentation of the hindgut (Tso and Crissinger, 2000). Fermentation involves the partial oxidation of a substrate via electron transfer in redox reactions, and microbes extract energy in the form of triphosphates (Muller, 2008). As non-starch polysaccharides bypass enzymatic action proximal to the ileocecal junction, microbes in the hindgut degrade polysaccharides to smaller polysaccharides and monosacchrides and are sequentially absorbed by bacteria (Muller, 2008). Oxidation of monosacchrides results in the formation of pyruvate, which can be oxidized to form volatile fatty acids

(VFA) such as acetate, proprionate, and butyrate (White, 2000). Release of VFAs into the lumen allows other microbes and intestinal tissue to utilize this source of energy. Colonic enterocytes efficiently absorb VFAs produced from hindgut fermentation of livestock (Barcroft et al., 1944). Researchers propose that VFAs can be retained by intestinal tissue via transporter-mediated absorption, such as MCT1 (an active transporter of VFAs), which is present in the intestines of pigs (Welter and Claus, 2008).

*Energy Value of Fiber and VFA*

The type of VFA produced from microbial fermentation determines its metabolism and utilization in mammals. Butyrate provides 28 ATP per mole and is usually absorbed and hydrolyzed in colon cells, serving as an energy source for cellular function (Wong et al., 2006; Blaxter, 1989). Butyrate has also been observed to regulate cell differentiation and proliferation, implying a physiological role of this VFA as it may potentially reduce the occurrence of colon cancer (Wong et al., 2006). Wong et al. (2006) revealed that propionate is mainly transported to the liver following hindgut absorption and metabolized to propionyl-CoA in gluconeogenesis. After absorption, acetate is metabolized in fatty acid synthesis or oxidized in ATP synthesis in adipose and muscle tissue (Elia and Cummings, 2007).

Energy produced by fermentation can account for 17% of the total digestible energy of diets fed to growing pigs and can supply up to 30% of the energy requirement for growing pigs (Shi and Noblet, 1993; Rerat et al., 1987). Dietary fiber can contribute up to 25% of the total digestible energy in diets to sows, implying that the ability of pigs

to utilize energy from fiber increases with age of the animal (Shi and Noblet, 1993; LeGoff and Noblet, 2001). This may be due to slower rate of passage of digesta in sows compared to young and growing pigs (Grieshop et al., 2001). With age, the large intestine and cecum increase in volume and house an extensive population of bacteria, which may improve NSP digestibility via greater fermentation (Pekas, 1991; Yen, 2001).

Along with the age, type and source of dietary fiber greatly impacts the energy value of ingredients. Water-soluble fiber, such as pectins, fructans, and beta-glucans , increases digesta viscosity when fed to nonruminants (Mosenthin et al., 2001). The increased viscosity of digesta with soluble fiber causes the surface area of the dietary material to swell and increase, allowing more opportunity for microbes to act on their substrates, which may lead to relatively high total tract digestibility of soluble fibers (Noblet and LeGoff, 2001). Urriola et al. (2010) observed that the apparent total tract digestibility (ATTD) of soluble fiber is comparably greater than the ATTD of insoluble fiber when pigs are fed corn by-products (92% vs. 41.3%, respectively). Increasing digesta viscosity has a two-fold effect on nutrient utilization. Soluble fiber suppresses contractions in the small intestine which can potentially reduce gut transit time and decrease the mixing of dietary particles with endogenous enzymes (Cherbut et al. 1990). This could result in decreased digestibility of fibrous and non-fibrous feed components in the midgut.

Lignin is a plant molecule that remains undigested by pigs, and no significant fermentation occurs by microbes in the hindgut (Graham et al., 1986; Shi and Noblet, 1993). Lignin functions by intertwining with cellulose in maturing plants, increasing the

rigidity of the plant structure. When mature plants are fed to nonruminants, this bound cellulose is less available for microbial attack and may pass through the hindgut with little or no fermentation (Shi and Noblet, 1993).

## Influence of Fiber on Gut Health and Nutrient Digestibility

### *Gut Health*

Feed ingredients affect the proliferation of specific bacteria in the hindgut of mammals (Jensen et al., 2003; Hedemanne et al., 2003). Containing high soluble fiber fractions, the inclusion of sugar beet pulp and wheat bran promotes proliferation of *C. leptum* and *C. coccoides* bacterial groups in growing pigs, which produce acetate and butryate from digestion of fermentable carbohydrates (Pieper et al., 2012). Alfalfa meal inclusion in swine diets promotes the proliferation of anaerobic and cellulolytic bacteria in the colon (Anugwa et al., 1989). Improved hindgut fermentation and greater short-chain fatty acid production can result from increased levels of cellulolytic bacteria and reduce the pH of gut digesta. This reduction in pH promotes the growth of bifidobacteria and lactobacillus bacteria, which inhibit the proliferation of pathogenic bacteria responsible for diarrhea (Bezkorovainy, 2001) and may increase health and performance of swine in various stages of production. Specific oligosaccharides can pass through the digestive tract of pigs undigested and inhibit the population of pathogenic bacteria, possibly improving the health of the animal (Pettigrew, 2000). Pettigrew et al. (2000) observed the action of mannan-oligosaccharides inhibiting E. coli colonization of epithelial tissue by binding to lectins on the bacterial cell wall.

When mannon-oligosaccharides bind to E. coli, the complex passes through the digestive tract and is excreted by the animal. Another study observed the impact that chito-oligosaccharide may have in improving the health of freshly weaned, *E. coli* – challenged barrows (Liu et al., 2010). The authors observed a reduction in scouring between the fiber-supplemented pigs and the *E.coli* – challenged control group. However, fiber supplementation did not reduce the population of E.coli in the challenged pigs, and growth performance was also not ameliorated. Therefore, this study concluded that fiber supplementation can mask scouring by increasing hindgut absorption of water, but not reduce the pathogen's impact on growth performance. Absorption of short-chained fatty acids (SCFA) promote sodium uptake and increases water reabsorption in the colon (Mosenthin et al., 2001). SCFA are readily absorbed by the GI tract and improves digestive and absorptive capacities in pigs (Rombeau and Kripke, 1990). Also, SCFA maintains the mucosal barrier lining of the gut, which prevents the infiltration of foreign bacteria in the digestive tract (Reardon and Tappenden, 1999). Collectively, these actions may reduce the occurrence of non-pathogenic diarrhea in pigs.

Mucin is secreted by goblet cells in the GI tract and lubricates and protects epithelial tissue from chemical and physical irritants as well as pathogenic bacterial attachment (Tanabe et al., 2006). Predominantly comprised of cysteine, proline, serine, and threonine, the mucin backbone is attached to oligosaccharide side chains that are resistant to endogenous digestion (Montagne et al., 2004). As little mucin is recovered in feces, it appears that much of the CP, AA, and carbohydrates in mucin is fermented in the hindgut (Lien et al., 2001). Several studies have shown that specific types of

dietary fiber increases mucin production. In weaned pigs, the production of mucin at the terminal ileum and the number of goblet cells per villus in the small intestine increased as carboxymethylcellulose, a non-fermentable, viscous ingredient, was fed (Piel et al., 2005). Beet pulp and pectin, also viscous ingredients, increased mucin production in the cecum and colon but not in the stomach or jejunum in pigs, implying that the viscosity, and not fermentability, of a fiber source may impact mucin secretion in the distal midgut and hindgut of pigs (Tanabe et al., 2006; Libao-Mercado et al., 2009).

Thus far, hindgut fermentation has been discussed as a beneficial response to pigs consuming fibrous ingredients. However, enhanced fermentation may not always result in an improved health status. According to Hampson et al. (2001), feeding pigs soluble fiber (sweet lupins) resulted in pigs becoming infected with swine dysentery by impacting microbial growth through pH alteration in the hindgut. Feeding a cooked rice-based diet with no added fiber prevented the pigs from developing dysentery, even when inoculated with *B. hyodysenteriae*. which is the causative organism for dysentery. The authors hypothesized that the diet lacking fermentable fiber created a punitive environment for the bacteria to colonize by reducing colonic pH. The researchers fed pigs another soluble fiber source, guar gum, and observed an increase in colonization of hemolytic E. coli in the small intestine of weaned pigs compared to the control group that was not fed guar gum.

*Nutrient Digestibility*

Through alteration of gut material viscosity and mucosal secretion, dietary fiber may influence the digestibility and absorption of feed components, including amino acids, lipids, carbohydrates, minerals, and energy. Inclusion of citrus and apple pectin at

8% of cornstarch and corn-based diets with soybean meal reduced the AID and SID of CP and AA (Mosenthin et al., 1994; Buraczewska et al., 2007). When carboxymethylcellulose was fed to pigs, the SID of CP and AA increased compared to other fiber diets (Fledderus et al., 2007). Being viscous and nonfermentable, carboxymethylcellulose increased mucin production and endogenous N loss without influencing ileal microbial populations (Piel et al., 2005). Increasing the NDF of diets containing wheat bran and soy hulls resulted in a reduction of AID and SID of most AA in growing pigs (Lenis et al., 1996; Dilger et al., 2004). However, feeding 10% barley straw and 13% cellulose did not impact AID or SID of CP and most AA (Sauer et al., 1991; Li et al., 1994), and cellulose was observed to not increase the endogenous loss of CP and AA (Li et al., 1994). Studies reveal that the viscosity of soluble fibers impact N and AA digestibility in pigs, and insoluble fibers can inhibit AA and CP digestion due to lignin and hemicellulose, but not the cellulose content of the fiber.

Along with AA digestibility, fiber can affect the digestion of lipids in nonruminants. Inclusion of beet pulp and soy hulls have reduced the AID and ATTD of dietary fat in pigs (Graham et al., 1986; Canh et al., 1998); whereas wheat bran has shown variable influence on lipid digestion (Wilfart et al., 2007; Graham et al., 1986). Wheat bran reduced the ATTD of fat in diets containing rapeseed oil and not in diets supplied with fish meal, which serves as an energy, fat, and CP source (Graham et al., 1986). The difference in source of dietary lipids may influence the interaction of fiber and lipid digestion.

Research has revealed that the solubility of fiber may influence dietary carbohydrate digestibility and absorption. Owusu-Asiedu et al. (2006) showed that guar

gum reduces plasma glucose concentration in pigs compared to diets supplemented with cellulose, and wheat bran does not appear to impact ATTD of starch (Wilfart et al., 2007). Researchers theorize that soluble fiber can decrease carbohydrate digestion by inhibiting glucose transfer between the lumen and epithelial tissue, reducing glucose absorption (Kritchevshy et al., 1988).

As previously mentioned, dietary fiber has the capacity to bind to minerals and organic compounds through interaction of free carboxyl groups and uronic acids (Oakenfull, 2001). Girard et al. (1995) showed that addition of soluble and insoluble fiber to corn-soybean meal diets reduced serum concentrations of calcium, phosphorus, copper, and zinc in sows. However, the feeding of wheat bran did not impact the ATTD of ash in pigs, with ash digestibility only decreasing when the total level of fiber in the diets was increased above 40% of the diet (Wilfart et al., 2007). More research is required to determine the impact of different sources of fiber on the digestibility of mineral and organic compounds in swine diets.

## Fiber in Swine Production

### *Growth Performance*

As the availability of nutritionally efficient grains is decreasing, researchers are beginning to seek methods for appropriate inclusion of NSP in swine diets. Understanding that the digestibility of fiber increases as nonruminants matures, producers are looking at fibrous ingredients to supply energy for growing pigs. Shriver et al. (2003) discovered that the growth performance of growing pigs from 60 to 250

pounds was unaffected with the inclusion of 10% soybean hulls. The authors included the soy hulls in a low protein, amino acid supplemented diet. In addition to no deleterious effect on body weight, the authors also observed that the soy hull diet resulted in leaner carcasses than the non-fiber, amino acid group. This observation is likely due an underestimation of net energy of the high fiber diet, resulting in less energy available for the pigs to deposit excess fat tissue. Finally, soy hulls did not affect the feed efficiency of the animals. Other researchers have seen similar, non-detrimental effects of feeding fibrous ingredients to growing pigs. Kornegay (1981) found that the growth performance of growing pigs from 50 to 185 pounds was not reduced when feeding soybean hulls, even at 15% of the diet. The same study revealed that increasing the inclusion of soybean hulls to 30% reduced the energy digestibility of the diet when fed to sows, implying a definite limit to the appropriate inclusion of fiber in swine diets.

In other studies, however, soybean hulls have been observed to reduce the amino acid digestibility of diets fed to growing pigs. Dilger et al. (2004) discovered that the apparent ileal digestibility of energy decreased as soy hulls were included at 9% of the diet and that the apparent and true ileal digestibility of several amino acids were also reduced with fiber inclusion. A reason for the different conclusions between this study and the previously mentioned studies may be in the formulation of the diets other than the fiber source. Shriver et al. (2003) and Kornegay (1981) fed corn-based, production diets to pigs, while Dilger et al. (2004) observed fiber effects on the nutrient digestibility of highly digestible, semi-purified diets. Therefore, an inhibitory effect of fiber inclusion may become more significant when observing the interaction of fiber with highly digestible feedstuffs.

According to the presented data, cellulose does not seem to have an adverse influence on nutrient bioavailability of nursery pig diets, whereas the use of other fiber types is limited in younger pigs. Also, the utilization of dietary fiber is improved in pigs as they increase in age and weight. Therefore, heavier pigs may be able to utilize a wider range of NSP than lighter pigs and that fiber may not be as deleterious towards nutrient absorption. Fortin et al. (2003) tested the ability for growing-finishing pigs to digest high fiber diets containing very high levels of soluble fiber. Diets formulated with 70% oat bran, which contains a significant beta glucan fraction, were fed to pigs from 115 and 240 pounds. Only minor effects were observed between the growth performance and carcass characteristics of the high-fiber and control groups. Another study demonstrated the effects of feeding insoluble and soluble fiber sources to growing-finishing pigs and observed little difference between the two fiber groups (Galassi et al. 2003). Sugar beet pulp was selected as the highly fermentable, soluble fiber source and wheat bran as the less fermentable, insoluble fiber source. As the pigs aged and increased body weight, fiber utilization improved. Even though nitrogen and energy digestibility decreased when sugar beet pulp and wheat bran were added to the diets, the authors observed similar carcass traits between the two fiber groups and the control group, including protein and fat deposition.

## Conclusions

The search for alternative feed ingredients and novel feeding strategies has led researchers to investigate the role of dietary fiber in nonruminant species. With extensive hindgut fermentation, pigs are viable candidates for applying such ingredients in commercial feeding programs. Many alternative feed ingredients are less nutrient-dense and contain more fiber content than conventional cereal grains. As the human population does not compete with livestock production for fibrous feedstuffs, researchers are investigating the possible application of high fiber diets in the swine industry. As previously discussed, dietary fiber has potential nutritive impact in pigs. The age, body weight, and production status of a pig influences its ability to utilize fiber. The classification of dietary fiber is fairly complex and inconsistent across the industry, as crude fiber, total dietary fiber, neutral detergent fiber, acid detergent fiber, and soluble and insoluble fiber fractions are all accepted as means for describing fiber. As more research is conducted in the use of dietary fiber in nonruminant diets, a consistent classification of fiber is required for appropriate application of the ingredients. Further analysis of high fiber ingredients and their fiber fractions is required as researchers investigate the influence that different fractions can have on energy utilization and nutrient digestibility. Therefore, the objectives of the studies discussed in this thesis were to determine:

1) The amino acid digestibility of alternative proteins sources in growing pigs.

2) The impact of dietary fiber on the energy, nitrogen, and amino acid digestibility of diets fed to growing pigs.

References

Almeida, F. N., J. K. Htoo, J. Thomson, and H. H. Stein. 2013. Amino acid digestibility in camelina products fed to growing pigs. Can. J. Anim. Sci. 93:335-343.

Anugwa, F. O. I., V. H. Varel, J. S. Dickson, W. G. Pond, and L. P. Krook. 1989. Effects of dietary fiber and protein concentrations on growth, feed efficiency, and visceral organ weights and large intestine microbial populations of swine. J. Nutr. 119:879-886.

AOAC, 2006. *Official Methods of Analysis*, 18th ed. Assoc. of Anal. Chemists, Arlington, VA.

Aufrere, J. and B. Michalet-Doreau. 1988. Comparison of methods for predicting digestibility of feeds. Anim. Feed. Sci. and Tech. 20:203-218

Barcroft, J., R. A. McAnally, and A. T. Phillipson. 1944. Absorption of VFA from the alimentary tract of the sheep and other animals. J. Exp. Biol. 20:120-132.

Bezkorovainy, A. 2001. Probiotics: determinant of survival and growth in the gut. Am. J. Clin. Nutr. 73(suppl):399S-405S.

Blaxter, K. L. 1989. Energy Metabolism in Animals and Man. Cambridge University Press. Cambridge, UK.

Boirie, Y., M. Dangin, P. Gachon, M. P. Vasson, J. L. Maubois, and B. Beaufrere. 1997. Slow and fast dietary proteins differently modulate postprandial protein accretion. Proc. Natl. Acad. Sci. U.S.A. 94:14930-5.

Buraczewska, L., E. Swiech, A. Tusnio, M Taciak, M. Ceregrzyn, and W. Korczynski. 2007. Theeffect of pectin in amino acid digestibility and digesta viscosity, motility and morphology of the small intestine, and on N-balance and performance of young pigs. Livest. Sci. 109:53-56.

Burkhalter, T. M., N. R. Merchen, L. L. Bauer, S. M. Murray, A. R. Patil, J. L. Brent Jr., and G. C. Fahey Jr. 2001. The ratio of insoluble to soluble fiber components in soybean hulls affects ileal and total-tract nutrient digestibilities and fecal characteristics of dogs. J. Nutr. 131:1978-1985

Canh, T. T., A. L. Sutton, A. J. Aarnink, M. W. Verstegen, , J. W. Schrama, and G. C. Bakker. 1998. Dietary carbohydrates alter the fecal composition and pH and the ammonia emission in slurry of growing pigs. J. Anim. Sci. 76:1887-1895.

CAST. 1999. Animal agriculture and global food supply. Task Force Rep. 135.

Carpenter, K. J. 2003 A short story of nutritional science: Part 4 (1945-1985). J. Nutr. 133:3331-3342.

Cervantes-Pahm, S. K. and H. H. Stein. 2010. Ileal digestibility of amino acids in conventional, fermented, and enzyme-treated soybean meal and in soy protein isolate, fish meal, and casein fed to wenling pigs. J. Anim. Sci. 88:2674-2683.

Cherbut, C., E., Albina, M. Champ, J. L. Doublier, and G. Lecannu. 1990. Action of guar gums on the viscosity of digestive contents and on the gastrointestinal motor functions in pigs. Digestion 46:205-213.

Cho, S., J. W. DeVries, and L. Prosky. 1997. Dietary fiber analysis and applications. AOAC Intl., Gaithersburg, MD.

Cromwell, G.L. 2000. Utilization of soy products in swine diets. Pages 258-282 in Soy in Animal Nutrition. J.K. Drackley, ed. Federation of Animal Sciences Societies, Savoy, IL

de Godoy, M., L. Bauer, C. Parsons, G. Fahey, Jr. 2009. Select corn coproducts from the ethanol industry and their potential as ingredients in pet foods. J Anim Sci. 87:189–199.

del Rio, J., J. Rencoret, P. Prinsen, A. Martinez, J. Ralph, and A. Gutierrez. 2012. Structural Characterization of Wheat Straw Lignin as Revealed by Analytical Pyrolysis, 2D-NMR, and Reductive Cleavage Methods. J. Agr. Food Chem. 60:5922-5935.

Dikeman, C. L., and G. C. Fahey Jr. 2006. Viscosity as related to dietary fiber. A review. Crit. Rev. Food Sci. Nutri. 45:649-663.

Dilger, R. N., J. S. Sands, D. Ragland, and O. Adeola. 2004. Digestibility of nitrogen and aminoacids in soybean meal with added soyhulls. J. Anim. Sci. 82:715-724.

During, K., P. Porsch, A. Mahn, O. Brinkmann, and W. Gieffers. 1999. The non-enzymatic microbicidal activity of lysozymes. FEBS Lett. 449:93–100.

Eastwood, L., P. R. Kish, A. D. Beaulieu, and P. Leterme. 2009. Nutritional value of flaxseed meal for swine and its effects on the fatty acid profile of the carcass. J Anim Sci 87:3607-3619.

Elia, M., and J. H. Cummings. 2007. Physiological aspects of energy metabolism and gastrointestinal effects of carbohydrates. Eur. J. Clin. Nutri. 61(Suppl 1):S40-74.

Enser M., Richardson R. I., Wood J. D., Gill B. P., Sheard P. R. 2000. Feeding linseed to increase the n-3 PUFA of pork: Fatty acid composition of muscle, adipose tissue, liver and sausages. Meat Sci. 55:201–212.

Fledderus, J., P. Bikker, and J. W. Kluess. 2007. Increasing diet viscosity using carboxymethylcellulose in weaned piglets stimulates protein digestibility. Livest. Sci. 109:89-92.

Falkowska, A., J. Falkowski, W. Kozera, D. Bugnacka. 2006. Nutrient digestibility and nitrogen balance in finishing pigs fed diets containing ground wheat straw. Polish J. Nat. Sci. 20:155-162.

FAO. Food and Agriculture Organization. 2008. International Year of the Potato.

Fortin, A., W. M. Robertson, S. Kibite, and S. J. Landry. 2003. Growth performance, ‘ carcass and pork quality of finisher pigs fed oat-based diets containing different levels of B-glucans. J. Anim. Sci. 81:449-456.

Galassi, G., G. M. Crovetto, L. Rapetti, and A. Tamburini. 2003. Energy and nitrogen balance in heavy pigs fed different fibre sources. Livest. Prod. Sci. 85:253-262.

Goldsmith, P. D. 2008. Economics of soybean production, marketing, and utilization. Pages 117–150 in Soybeans: Chemistry, Production, Processing and Utilization. L. A. Johnson, P. J.White, and R. Galloway, ed. AOCS Press, Urbana, IL.

Gonzalez-Vega, J. C. and H. H. Stein. 2012. Amino acid digestibility in canola, cottonseed, and sunflower products fed to finishing pigs. J. Anim. Sci. 90:4391-4400.

Girard, C. L., S. Robert, J. J. Matte, C. Farmer, G. P. Marineaub. 1995. Influence of high fibre diets given to gestating sows on serum concentrations of micronutrients. Livest. Prod. Sci. 43:15-26.

Graham, H., K. Hesselman, and P. Aman. 1986. The influence of wheat bran and sugar-beet pulp on the digestibility of dietary components in a cereal-based pig diet. J. Nutr. 116:242-251.

Grieshop, C. M., D. E. Reese, and G. C. Fahey, Jr. 2001. Nonstarch polysaccharides and oligosaccharides in swine nutrition. Page 107 in Swine Nutrition. A. J. Lewis and L. L. Southern, Eds. CRC Press, Boca Raton, FL.

Grieshop, C. M., C. T. Kadzere, G. M. Clapper, E. A. Flickinger, L. L. Bauer, R. L. Frazier, and G. C. Fahey. 2003. Chemical and nutritional characteristics of United States soybeans and soybean meals. J. Agric. Food Chem. 51:7684-91.

Hampson, D. J., J. R. Pluske, and D. W. Pethick. 2001. Dietary manipulation of enteric disease. In: Digestive Physiol of Pigs, Eds. J.E. Lindberg, B. Ogle. CABI Publishing, New York. Pg. 247-261.

Hansen, J. A., J. L. Nelssen, R. D. Goodband, and T. L. Weeden. 1993. Evaluation of animal protein supplements in diets for early-weaned pigs. J. Anim. Sci. 71:1853–1862.

Hedemann, M. S., C. M. Roentved, H. N. Laerke, B. M. Damgaard, B. B. Jensen, and K. E. Bach Knudsen. 2003. The effect of long-term peroral administration of Samlnoella typhumurium endotoxin and diets with contrasting carbohydrate composition on selected physiology and immunological parameters. Proc. 9th Int. Simp. Dig. Physiol. in Pigs, Banff, AB, Canada. 2:114-116.

IOM. 2006. Institute of Medicine. Dietary, functional, and total dietary fiber. Pages 340-421 in *Dietary Reference Intakes*. National Academies of Press, Washington, D.C.

Jensen, B. B., O. Hojberg, L. L. Mikkelsen, M. S. Hedemann, and N. Canibe. 2003. Enhancing intestinal function to treat and prevent intestinal disease. Proc 9th Int. Symp. Dig. Physiol. in Pigs, Banff, AB, Canada. 1:103-119.

Johnston, L. J., S. Noll, A Renteria, and J. Shurson. 2003. Feeding by-products high in concentration of fiber to nonruminants. Presented at Third National Symposium on Alternative Feeds for Livestock and Poultry.

Kornegay, E. T. 1981. Soybean hull digestibililty by sows and feeding value for growing-finishing swine. J. Anim. Sci. 53:138-145.

Kritchevsky, D. 1988. Dietary Fiber. Ann. Rev. Nutr. 8:301-328.

LeGoff, G. and J. Noblet. 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79:2418-2427.

Lenis, N. P., P. Bikker, J. van der Meulen, J. T. M. van Diepen, J. G. M. Bakker, and A. W. Jongbloed. 1996. Effect of dietary neutral detergent fiber on ileal digestibility and portal flux of nitrogen and amino acids and on nitrogen utilization in growing pigs. J. Anim. Sci. 74:2678-2699.

Li, D. F., J. L. Nelssen, P. G. Reddy, F. Blecha, R. D. Klemm, D. W. Giesting, J. D. Hancock, G. L. Allee, R. D. Goodband. 1991. Measuring suitability of soybean products for early-weaned pigs with immunological criteria. J. Anim. Sci. 69:3299–3307.

Li, S., W. C. Sauer, and R.T. Hardin. 1994. Effect of dietary fibre level on amino acid digestibility in young pigs. Can. J. Anim. Sci. 74:327-333.

Libao-Mercado, A. J. O., C. L. Zhu, J. P. Cant, H. Lapierre, J. N. Thibault, B. Seve, M. F. Fuller, and C. F. M. de Lange. 2009. Dietary and endogenous amino acids in pigs. J. Agroc. Food Chem. 46:1927-1934.

Lien, K. A., W. C. Sauer, and H. E. He. 2001. Dietary influences on the secretion into and degradation of mucin in the digestive tract of mongastric animals and humans. J. Anim. Feed Sci. 10:223-245.

Liu, P., X. S. Piao, P. A. Thacker, Z. K. Zeng, P. F. Li, D. Wang, and S. W. Kim. 2010. Chito-oligosacchartide reduces diarrhea incidence and attenuate the immune response of weaned pigs challenged with *Escheria coli* K88. J. Anim. Sci. 88:3871-3879.

Masood A., Stark K., Salem N. 2005. A simplified and efficient method for the analysis of fatty acid methyl esters suitable for large clinical studies. J. Lipid Res. 46:2299–2305.

Montagne, L., C. Piel, J. P. Lalles. 2004. Effect of diet on mucin kinetics and composition: Nutrition and health implications. Nutr. Rev. 62:105-114.

Montagne, L., J. R. Pluske, and D. J, Hampson. 2003. A review of interactions between fibre and the intestinal mucosa, and their consequences on digestive health in young nonruminant animals. Anim. Feed. Sci. Tech. 108:95-117.

Moon, H. K., J. W. Kim, K. N. Heo, Y. H. Kim, S. W. Kim, C. H. Kwon, I. S. Shin, and I. K. Han. 1994. Growth performance and amino acid digestibilities affected by various plant protein sources in growing-finishing pigs. Asian-Australas. J. Anim. Sci. 7:537–546.

Mosenthin, R., E. Hambrecht, and W. C. Sauer. 2001. Utilisation of different fibres in pigs feeds. In: Recent Develop. In Pig Nutrition 3. Eds. P. C. Gransworthy and J. Wiseman. Nottingham University Press.

Mosenthin, R., W. C. Sauer, and F. Ahrens. 1994. Dietary pectin's effect on ileal and fecal amino acid digestibility and exocrine pancreatic secretions in growing pigs. J. Nutr. 124:1222-1229

Muller, V. 2008. Bacterial Fermentation. *Pages 1-8 Encyclopedia of Life Sciences*. John Wiley & Sons. Ltd. Chichester. Doi: 10.1002/9780470015902.a0001415.pub2.

Newkirk, R.W., H. L. Classen,, T. A. Scott, and M. J. Edney. 2003. The digestibility and content of amino acids in toasted and non-toasted canola meals. Can. J. Anim. Sci. 83:131-139.

Noblet, J. and G. LeGoff. 2001. Effect of dietary fibre on the energy value of feeds for pigs. Anim. Feed Sci. Technol. 90: 35-52.

Oakenfull, D. 2001. Physical chemistry of dietary fiber. Pages 33 – 47 in *Dietary Fiber in Human Nutrition*. 3rd ed. G. A. Spiller, ed. CRC Press, Boca Raton, FL.

Oil World, 2011. Major meals, World summary balances. Oil World Weekly, February 28, 2011, 54: 95-104.

Owusu-Asiedu, A., J. F. Patience, B. Laarveld, A. G. Van Kessel, P. H. Simmins, and R. T. Zijlstra. 2006. Effects of guar gum and cellulose on digesta passage rate, ileal microbial populations, energy and protein digestibility, and performance of grower pigs. J. Anim. Sci. 84:843-852.

Owen, K. Q., J. L. Nelssen, R. D. Goodband, M. D. Tokach, L. J. Kats, and K. G. Friesen. 1995. Added dietary methionine in starter pig diets containing spray-dried blood products. J. Anim. Sci. 73:2647–2654.

Pekas, J. C. 1991. Digestion and absorption capacity and their development. Page 37 in Swine Nutrition. E. R. Miller, D. E. Ullrey, and A. J. Lewis Eds. Butterworh-Heinemann, Boston.

Pettigrew, J. E. 2000. Bio0Mos effects on pigs performance: A review. In: Biotechnology in the Feed Industry, Proc. Alltech 16th Annual Sym. Pg. 31-44.

Piel, C., L. Montagne, B. Seve, and J. P. Lalles. 2005. Increasing digesta viscosity using carboxymethylcellulose in weaned piglets stimulates ileal goblet cell numbers and maturation. J. Nutri. 135:86-91.

Pieper, R., S. Kroger, J. Richter, J. Wang, L. Martin, J. Bindelle, J. Htoo, D. von Smolinski, W. Vahjen, J. Zentek, and A. Van Kessel. 2012. Fermentable fiber ameliorates fermentable protein-induced changes in microbial ecology, but not the mucosal response, in the colon of piglets. J. Nutr. 141:661-667.

Reardon, K. and K. A.Tappenden. 1999. Enhancement of intestinal adaptation with short-chain fatty acid supplemented total parenteral nutrition in neonatal piglets. FASEB J 13:A217(abs.).

Rerat, A., M. Fiszlewicz, A. Giusi, and P. Vaugelade. 1987. Influence of meal frequency on postprandial variations in the production and absorption of volatile fatty acids in the digestive tract of conscious pigs. J. Anim. Sci. 64:448-456.

Rombeau, J. L and S. A. Kripke. 1990. Metabolic and intestinal effects of short-chain fatty acids. J. Parenter. Enteral Nutr. 14:181S-185S.

Ryhanen, E. L., S. Perttila, T. Tupasela, J. Valaja, C. Eriksson, and K. Larkka. 2007. Effect of Camelina sativa expeller cake on performance and meat quality of broilers. J. Sci. Food Agric. 87:1489-1494.

Saha, Badal C. 2003. Hemicellulose bioconversion. J. Ind. Microbiol. Biotechnol. 30: 279-291.Salanti, , A., L. Zoia, M. Orlandi, F. Zanini, G. Elegir. 2010. Structural Characterization and Antioxidant Activity Evaluation of Lignins from Rice Husk. J. Agric. Food Chem. 58: 10049–10055.

Sauer, W. C., R. Mosenthin, F. Ahrens, and L. A. den Hartog. 1991. The effect of source of fiber on ileal and fecal amino acid digestibility and bacterial nitrogen excretion in growing pigs. J. Anim. Sci. 69:4070-4077.

Schmidt, L. S., C. M. Nyachoti, and B. A. Slomiski. 2003. Nutritional evaluation of egg byproducts in diets for early-weaned pigs. J. Anim. Sci. 81:2270-2278.

Shelton, D. R. and W. J. Lee. 2000. Cereal carbohydrates. Page 385-316 in *Handbook of Cereal Science and Technology*. 2nd ed. K . Kulp and J. G. Ponte, eds. Marcel Dekker, New York, NY.

Shi, X. S. and J. Noblet. 1993. Contribution of the hindgut to digestion of diets in growing pigs and adult sows: Effect of diet composition. Livest. Prod. Sci. 34:237-252.

Shriver, J. A., S. D. Carter, A. L. Sutton, B. T. Richert, B. W. Senne, and L. A. Petty. 2003. Effects of adding fiber sources to reduced-crude protein, amino acid-supplemented diets on nitrogen excretion, growth performance, and carcass traits of finishing pigs. J. Anim. Sci. 81:492-502.

Simopoulos A. P. 1999. Essential fatty acids in health and chronic disease. Am. J. Clin. Nutr. 70(Suppl.):560S–569S.

Smith, D. B., J. G. Roddick, J. L. Jones. 1996. Potato glycoalkaloids: some unanswered questions. Trends in Food Science and Technology 7, 126–131.

Smith, K. 1986. Advances in feeding soybean products. Pages 189–194 in Proc. World Conf. Emerging Technol. in the Fats andOils Ind. A. R. Baldwin, ed. AOAC Press, Urbana, IL.

Tanabe, H., H. Ito, K. Sugiyama, S. Kriryama, and T. Morita. 2006. Dietary indigestible components exert different regional effects on luminal mucin secretion through their bulk-forming property and fermentability. Biosc. Biotechnol. Biochem. 70:1188-1194.

Tolman, R., and M. Tumbleson. 2006. Raising American Standards— World of Corn. Natl. Corn Growers Assoc. www.ncga.com/WorldOfCorn/main/environmental.asp.

Trowell, H., D. A T. Southgate, T. M. S. Wolever, A. R. Leeds, M. A. Gassul, and D. J. A. Jenkins. 1976. Dietary Fibre redefined. Lancet 1:967.

Tso, P., and K. Crissinger. 2000. Overview of digestion and absorption. Pages 75-106 in *Biochemical and Physiological Aspects of Human Nutrition.* M. H. Stipanuk, ed. Sounders, Philadelphia, PA

Tusnio, A, Pastuszewska, B, Święch, E, Buraczewska, L 2007. The effect of potato protein and potato fibre on amino acid digestibility, small intestinal structure and on N-balance and performance of young pigs. In Energy and protein metabolism and nutrition (ed. I Ortigues-Marty, N Miraux and W Brand-Williams), pp. 441–442. EAAP publication No. 124, Vichy, France.

Urriola, P. E., G. C. Shurson, and H. H. Stein. 2010. Digestibility of dietary fiber in distillers coproducts fed to growing pigs. J. Anim. Sci. 88:2373-2381.

Veum, T. L., J. D. Crenshaw, T. D. Crenshaw, G. L. Cromwell, R. A. Easter, R. C. Ewan,J. L. Nelssen, E. R. Miller, J. E. Pettigrew, and M. R. Ellersieck. 2009. The addition of ground wheat straw as a fiber source in the gestation diet of sows and the effect on sow and litter performance for three successive parities. J. Anim. Sci. 87: 1003-1012

von Heimendahl E., G. Breves, and H. J. Abel. 2010. Fiber related digestive processes in three different breeds of pigs. J. Anim. Sci. 88:972–981.

Welter, H. and R. Claus. 2008. Expression of the monocarboxylate transporter 1 (MCT1) in the cells of porcine intestine. Cell Biol. Int. 32:638-645.

White, D. 2000. The Physiology and Biochemistry of Prokaryotes. 2nd ed. Oxford University Press. New York, NY.

Wilfart, A., L. Montagne, H. Simmins, J. van Milgen, and J. Noblet. 2007. Sites of nutrient digestion in growing pigs: Effects of dietary fiber. J. Anim. Sci. 85:976-983.

Wong, J. M., R. de Souza, C. W. Kendall, A. Emam, and D. J. Jenkins. 2006. Colonic health: Fermentation and short chain fatty acids. J. Clin. Gastroenterol. 40:235-243.

Yen, J. T. 2001. Anatomy of the digestive system and nutritional physiology. Page 31 in Swine Nutrition 2nd ed. A. J. Lewis and L. L. Southern eds. CRC Press, Boca Raton, FL.

# CHAPTER 2.
# INVESTIGATING THE AMINO ACID DIGESTIBILITY OF ALTERNATIVE PROTEIN SOURCES IN GROWING PIGS

## Abstract

Three experiments were designed to quantify the nitrogen (N) and amino acid (AA) digestibility of various protein sources fed to growing pigs. The protein ingredients were sunflower meal, cottonseed meal, canola meal, camelina meal, egg albumen, casein, blood meal, plasma meal, potato protein concentrate, soy protein concentrate, soy protein isolate, and linseed meal, which were fed as the sole source of amino acids for the animals and were included in semi-purified, corn starch-based diets. A semi-purified, nitrogen-free diet (NFD) was used to estimate endogenous losses of AA. In each experiment, pigs were surgically fitted with a simple T-cannula at the distal ileum and fed four experimental diets and the NFD based on a 5 X 2 crossover arrangement in a randomized crossover design, with 5 diets and 2 periods. For experiment 1 (Exp. 1), sunflower meal, cottonseed meal, canola meal, and camelina meal were fed to 19, 42-kg barrows to determine their apparent (AID) and standardized (SID) digestibility of AA at the terminal ileum. The AID and SID of N and all AA were greatest for sunflower meal ($P < 0.05$), and canola meal revealed similar AID and SID of N, Met, Thr, Leu, and Val. The AID and SID of all essential AA, except for Met and Trp, was lower than sunflower meal ($P < 0.05$). Cottonseed meal had lower AID and SID for Lys, Ile, Leu,

Met, Thr, and Val than the other protein sources ($P < 0.05$). In experiment 2 (Exp. 2), egg albumen, casein, blood meal, and plasma meal were fed to 20, 20-kg barrows to determine the AID and SID of N and AA. The AID and SID of N and indispensable AA was greatest for casein compared to the other ingredients ($P < 0.05$). Blood meal, plasma meal, and egg albumen had similar AID and SID of many AA; however, egg albumen did have the greatest AID and SID of Cys among ingredients, while plasma meal had greater AID and SID of Thr than blood meal ($P < 0.05$).. For experiment 3 (Exp. 3), potato concentrate, soy concentrate, soy isolate, and linseed meal were fed to 20, 25-kg barrows. The AID and SID of N was similar for potato concentrate, soy concentrate, and soy isolate and greater than linseed meal ($P < 0.05$). The AID and SID of Leu and Thr were greater in potato protein concentrate than soy concentrate ($P < 0.05$), and AID and SID of Thr was lower in soy isolate than potato concentrate. The apparent and standardized digestibility of all essential amino acids was similar between soy isolate and soy concentrate, and only the AID and SID of Asp was greater in soy isolate that soy concentrate ($P < 0.05$). Linseed meal revealed the lowest AID and SID of N and AA digestibility among protein sources ($P < 0.05$) in this experiment. In conclusion, animal protein and plant protein concentrates reveal the highest AID and SID of N and AA, and the digestibility of N and AA vary greatly among oilseed meals.

Key words: Amino acids, growing pigs, nitrogen, protein

## Introduction

Soybeans, cottonseeds, canola, and sunflowers are the four most produced oil seeds in the world (Oil World, 2011). Soybean meal (SBM) is an ideal protein source for swine diets as the AA profile is complementary to cereal, being rich in Lys, Thr, and Trp (Gonzalez-Vega and Stein, 2012). As the demand increases for SBM, the availability reduces for animal producers, resulting in an increased need for alternative feed ingredients. Unfortunately, the AA profile and digestibility of many alternative ingredients are generally poorer than SBM when fed to pigs (Smith, 1986; Moon et al., 1994). Possible sources of protein to be fed to swine include oilseed meals, animal-derived protein ingredients, and plant protein concentrates.

Alternative oilseed meals to SBM include canola, cottonseed, sunflower, camelina, and linseed (flaxseed). Canola meal is the 2$^{nd}$ most produced oilseed meal in the world (Oil World, 2011) and has successfully been used as a replacement for soybean meal in growing pigs (Keith and Bell, 1982). Cottonseed meal, a readily available oilseed meal in the United States, is characterized by a rich profile of AA; however, cottonseed meal can also contains high levels of fiber and gossypol, which negatively impacts its nutritional value (Gonzalez-Vega and Stein, 2012; Tanksley, 1990; Chiba, 2001). Though sunflower meal may contain significant levels of dietary fiber and lignin that can impede AA digestibility, it has recently been shown to be readily digestible in growing-finishing pigs (Gonzalez-Vega and Stein, 2012; Perez et al., 1986). Camelina is an older crop grown in European nations and has regained nutritional interest due to its high omega-3 fatty acid content. Almeida et al. (2013)

showed that the CP and AA digestibility of camelina meal is comparable to canola meal when fed to growing pigs. Linseed meal has been shown to increase linolenic acid deposition in pigs and may be a viable source of nutrients in the swine industry (Enser et al., 2000). However, the AA digestibility has not been well researched, resulting in little understanding of appropriate inclusion of linseed meal.

Common animal-derived protein concentrates that have been used in swine nutrition are blood meal, blood plasma, and casein, which have been shown to be very digestible when fed to pigs (Cervantes-Pahm et al., 2010; Hansen et al., 1993). Another potential protein supplement is egg albumen, which has been not been well investigated in swine nutrition. One study has observed the AA digestibility of egg albumen to be similar to plasma meal (Schmidt et al., 2003). As the use of animal-derived proteins may be limited by consumer regulations and desire, researchers are also investigating the use of plant protein concentrates in livestock production. Plant protein concentrates that may be applied to swine production are potato protein concentrate, soy protein concentrate, and soy protein isolate. Production of these concentrates involves removal of carbohydrate, lipid, and fibrous components, which may impact AA digestibility. Researchers have shown that plant protein concentrates are often readily digestible when fed to young and growing pigs (Li et al., 1991; Smith et al., 1996).

Due to a dearth of information on the SID and AID of AA in the previously discussed ingredients, three experiments were conducted to investigate the AID and SID of N and AA of these protein ingredients when fed to growing pigs.

## Materials and Methods

All experimental protocols were approved by the Purdue Animal Care and Use Committee.

### Experimental design

Hampshire × Duroc × Yorkshire × Landrace barrows (Exp. 1 BW: 42 ± 0.70 kg; Exp. 2 BW: 20 ± 0.28 kg; Exp. 3 BW: 25 ± 0.25 kg) were obtained from the Purdue University Animal Research farm and used in a randomized crossover design with initial body weight as the blocking factor. Pigs were housed individually in floor pens with ad libitum access to water and 12 h of artificial lighting in climate controlled rooms (22$^{o}$C). At the beginning of each period, pigs were weighed and allotted to block by body weight and treatment within each block. Experimental diets were fed to the pigs (19 pigs for Exp. 1; 20 pigs for Exp. 2 and 3) according to a 5 × 2 crossover arrangement with each period lasting 7 d with controlled randomization such that pigs did not receive the same diet in Period 2 as Period 1. Five days were allowed for the pigs to adapt to the experimental diets, followed by a 2 d collection period of ileal digesta by attaching a plastic tubular bag to the externalized T-cannula on d 6 and 7. To reduce proliferation of bacteria in the ileal samples, each bag contained 10 mL of 5% formic acid, and ileal contents were stored at -20$^{o}$C between collections. Following the experiments, the ileal digesta was thawed and pooled for each pig for the 2 d collection, subsampled, and lyophilized. Daily feed allowance was given at 4% of BW of the smallest pig in each block at the beginning of the adaptation period, and feed was given in 2 equal portions at 0600 and 1800. Chromic oxide was incorporated into diets at 5 g/kg (as-fed basis) to calculate nutrient digestibility according to the index method .

Dietary Treatments

For each experiment, four diets were formulated to contain 16% CP (Exp. 1) or 19% CP (Exp. 2 and 3) with the experimental protein ingredient supplying all of the dietary AA. Cornstarch was adjusted to account for the inclusion of the protein source. A nitrogen-free, semi-purified, cornstarch-based diet was fed to determine the endogenous flow of AA. Diets were formulated to meet current NRC requirements (2012). Over 2 periods, there were 8 replicates per experimental and nitrogen-free diet. For Exp. 1, the experimental diets consisted of sunflower meal, cottonseed meal, canola meal, and camelina meal-based diets, which were fed at 523 g/kg, 392 g/kg, 420 g/kg, and 422 g/kg of the diets, respectively (as-fed basis) (Table 2.1). Exp. 2 consisted of diets containing egg albumen, casein, blood meal, and plasma meal, which were included at 233 g/kg, 212 g/kg, 213 g/kg, and 243 g/kg, respectively (as-fed basis) (Table 2.2). For Exp. 3, potato protein concentrate, soy protein concentrate, soy protein isolate, and linseed meal were fed at 237 g/kg, 290 g/kg, 223 g/kg, and 568 g/kg, respectively (as-fed basis) (Table 2.3).

Cannulation Surgery

The cannulation procedure follows that described previously by Dilger et al. (2004) Pigs were fasted for 18 to 24h before being fitted with metallic ileal cannulas at the distal ileum, approximately 6 cm proximal to the ileocecal junction. A Telazol mixture (containing 50 mg/mL each of tilet-amine HCl, zolazepam HCl, ketamine HCl [Fort Dodge Laboratories, Fort Dodge, IA], and xylazine HCl [Bayer Corp., Shawnee Mission, KS]) was administered intramuscularly at a dosage of 22.0 µL/kg of body weight to induce anesthesia of the pigs. After Telazol administration, the barrows were

maintained under gas anesthesia with Halothane gas (Halocarbon Laboratories, River Edge, NJ) at 1.5 to 2.0% with an oxygen flow rate of 2.0L/min. Antibiotic therapy (Polyflex [ampicillin trihydrate]) given intramuscularly at 11.0 mg/kg body weight) was administered before and after the surgery in order prevent infection and alleviate the need for antibiotic treatment during the recovery period

A longitudinal incision was made on the intestine, and the cannula was inserted into the ileum and secured with a continuous suture that extended to the barrel of the cannula. A circular defect was created in the body wall to allow the cannula to be exteriorized caudal to the last rib. Using a string attached to a bullet-shaped device threaded onto the cannula, the device and cannula was pulled through the defect and positioned appropriately. This method ensured that the structural integrity of the inserted cannula was not compromised. To secure the externalized cannula, a retainer plate and cap was secured onto the cannula barrel. Pigs were allowed at least 7 days to recover from the procedure before the start of the study. During recovery, the pigs were offered small amounts of a corn-soybean meal based diet, which satisfied or exceeded their nutrient requirements (NRC, 2012). Amount of feed offered was increased as the recovery improved with the pigs increasing in activity and appetite.

Chemical Analyses

Diets, ingredients, and freeze-dried ileal samples were ground to pass through a 0.5-mm screen before analysis. Diets and ingredients were analyzed for dry matter, energy, chromium, nitrogen, phosphorus, calcium, and amino acids. Ileal samples were analyzed for dry matter, chromium, nitrogen, and amino acids. Amino acid analyses were conducted at the Experimental Station Chemical Laboratory at the University of

Missouri. For AA analysis, samples were hydrolyzed using 6 *N* HCl at 100°C for 24h under nitrogen atmosphere. For the sulfur amino acids (methionine and cysteine), performic acid oxidation occurred prior to acid hydrolysis. Barium hydroxide was used to hydrolyze tryptophan during analysis. HPLC after postcolumn derivatization was used to determine amino acid concentrations in hydrosylate (AOAC, 2000; 982.30 E [a, b, c]). Chromium concentration of the samples were determined by digesting the material in perchloric/nitric acids and measured by the plasmic atomic emission spectroscopy method (AOAC, 2000: 990.08). The nitrogen content of the samples was determined by the Kjeltech method (Kjeltech 2300 Analyzer Unit, Hoganas, Sweden) following sulfuric acid digestion and by the combustion method (LECO FP Analyzer Model 602600, Leco Corp. Meriden, CT). Dietary calcium was determined by flame atomic absorption spectroscopy (Varian FS240, Varian Inc., Can Palo, CA), and phosphorus concentration was determined using ammonium molybdate according to Onyango et al. (2004). Dietary and ingredient gross energy was determined by adiabatic bomb calorimeter (Parr 1261 bomb calorimeter; Parr Instruments Co., Moline IL).

Calculations

In accordance with calculations described by Dilger et al. (2004), basal endogenous loss of AA can be determined with the index method using the following equation:

$$BEL = No \times (Cr_I/Cr_O)$$

where $N_O$ is the nutrient concentration of the nitrogen-free group of pigs, $Cr_I$ refers to the chromium concentration of the nitrogen-free diet, and $Cr_O$ represents the chromium concentration of the ileal output from pigs fed the nitrogen-free diet. The endogenous

losses of N and AA of these pigs were averaged to correct apparent ileal digestibility. Apparent ileal digestibility (AID) was calculated with the following equation:

$$AID = [1- (Cr_I/Cr_o) \times (N_O/N_I)] \times 100$$

where $Cr_I$ is the chromium concentration of the diet consumed, $Cr_O$ represents the chromium concentration of the ileal output, $N_O$ is the nutrient output (N, AA, or energy) in the ileal digesta, and $N_I$ refers to the nutrient concentration of the diet consumed. Standardized ileal digestibility (SID) can be calculated from the following equation:

$$SID = AID + [(BEL/N_i) \times 100]$$

where AID is the apparent ileal nutrient digestibility, BEL is the basal endogenous loss of nutrient, and $N_i$ is the nutrient concentration of the diet.

Statistical Analysis

Data was analyzed using the MIXED procedure of SAS (2012) appropriate for randomized crossover design, with pig serving as the experimental unit. The model included the fixed effects of the diet, and period and pig were random effects. Means were calculated using the LSMEANS statement. Means were separated using the PDIFF option when significant *F*-tests for treatment were observed. An α value of 0.05 was used to determine significant differences among means.

## Results

### Composition of Diets and Ingredients

Diets in Exp. 1 were formulated to provide 160 g/kg of CP and contain a Ca:P ratio of 1.2 (Table 2.4). Due to variability of the experimental ingredients, the diets

differed slightly compared to the formulation based on ingredient analysis provided in the NRC (2012) (Table 2.5). Sunflower meal analysis revealed slightly greater CP, GE, Ca, and P content than that described in the NRC (2012), while AA analysis revealed very similar values. Analysis of cottonseed meal showed similar nutrient values as those listed in the NRC (2012), except for a slighter greater concentration of CP in the experimental cottonseed meal. Our analysis of AA revealed similar or slightly greater concentrations for the majority of AA compared to the NRC (2012); however, our analysis revealed lower Trp and Cys than that listed in the NRC (2012) (Trp: 3.0 g/kg compared to 5.3 g/kg; Cys: 6.6 g/kg compared to 8.2 g/kg). As canola meal is a well-defined ingredient in swine nutrition, the analysis of the experimental canola meal consisted of a similar nutrient profile as that provided in the NRC (2012). A fairly new ingredient in swine nutrition, camelina meal analysis revealed similar nutrient content as that listed in the NRC (2012), except for an over estimation of Met and Cys content (Met: 6.0 g/kg compared to 8.7 g/kg; Cys: 7.0 g/kg compared to 9.5 g/kg).

Table 2.6 shows the nutrient and energy values for diets in Exp. 2. Diets were formulated to contain 189 g/kg of CP and provide Ca and P at a ratio of 1.2. The test ingredients egg albumen, casein, blood meal, and plasma meal were analyzed for nutrients previously discussed (Table 2.7). The egg albumen analysis provided in this experiment provides essential information for current and future research, as egg albumen is not characterized in the NRC (2012). Casein was analyzed to contain similar or slightly greater energy and nutrients as that described in the NRC (2012). The analyses of blood meal and plasma meal were similar for all nutrients and energy

compared to the NRC (2012), which underestimated the CP and majority of AA in the experimental blood meal.

Diet analysis for Exp. 3 is provided in Table 2.8, in which diets were formulated similar to those described for Exp. 2, and analysis of potato protein concentrate, soy protein concentrate, soy protein isolate, and linseed meal was performed (Table 2.9). The majority of the nutrient analysis of potato protein concentrate matches that listed in the NRC (2012). However, the CP content is much greater according to the NRC (2012), with our analysis of CP being 695 g/kg and the NRC CP listed as 798 g/kg. This difference may be attributed to a much lower Val content in the experimental ingredient (Val: 11.7 g/kg compared to 53.6 g/kg). Other than an inconsistency in Val content (experimental Val: 8.9 g/kg compared to 31.4 g/kg), analysis of soy protein concentrate is similar to NRC (2012) values. Analysis of soy protein isolate revealed a similar nutrient profile compared to the NRC (2012), except for an overestimation by the NRC for CP, Val, and Ser content (CP: 696 g/kg compared to 848 g/kg; Val: 9.9 g/kg compared to 40.2 g/kg; Ser: 36.7 g/kg compared to 43.7 g/kg. Analysis of linseed meal revealed greater CP and GE content than NRC (2012) values (CP: 391 g/kg compared to 332 g/kg; GE: 5956 kcal/kg compared to 4887 kcal/kg), and the AA profile of experimental linseed meal was greater for nearly all AA.

Endogenous Loss of AA

As previously described, endogenous loss of AA was determined through feeding a nitrogen-free diet in order to calculate the SID of AA, which should provide a more accurate understanding of AA digestibility than AID. Tables 2.10 to 2.12 reveal similar endogenous loss of N and AA between Exp. 1 and Exp. 2, with less loss of AA

in Exp.3, even though the pigs in Exp. 3 were of similar maturity as those in Exp. 2. This reveals that a large range of variability exists in determining endogenous amino acid loss in pigs. There appears to be a greater loss of Pro, and sometimes, Gly, in the natural loss of AA in pigs, which results in an overestimation of SID of Pro and Gly in many diets fed to pigs. To determine accurate digestibility of Pro and Gly, researchers should reference the AID of those AA.

AID and SID of N and AA in Exp.1

Among all treatments, the source of protein significantly impacted AID and SID of N and all AA other than Trp and Pro (Tables 2.13 and 2.14). Sunflower meal had the greatest AID and SID of N and all AA among ingredients, with greater AID and SID of Arg than canola meal ($P < 0.05$). Canola meal had greater AID and SID of His, Ile, Leu, Lys, Met, Phe, Thr, Val, and many dispensable AA compared to camelina meal and cottonseed meal ($P < 0.05$). Camelina meal had greater AID and SID of His, Ile, Leu, Lys, Met, Thr, and Val than cottonseed meal, which was observed to have the lowest AID and SID of N and AA among ingredients ($P < 0.05$).

AID and SID of N and AA for Exp. 2

Casein was revealed to have the greatest AID and SID of N and AA among ingredients in Exp. 2 (Tables 2.15 and 2.16) as the AID and SID of N and all indispensable AA was greater in casein than the other diets ($P < 0.05$). The AID and SID of Arg, Ile, and Thr in egg albumen was greater than in blood meal, and the AID and SID of Cys was greater than in casein and blood meal ($P < 0.05$). Similar to egg albumen, plasma meal also had greater AID and SID of Arg, Ile, and Thr than in blood meal and greater AID and SID of Cys than in casein and blood meal, ($P < 0.05$).

Though the AID of His was greater in blood meal than in egg albumen and plasma meal, blood meal had the lowest AID of many AA among ingredients ($P < 0.05$).

AID and SID of N and AA for Exp. 3

In Tables 2.17 and 2.18, the AID and SID of N and AA are compared among plant protein concentrates and linseed meal. Potato protein had greater AID and SID of Thr compared to soy protein isolate ($P < 0.05$) and similar AID and SID of N and all other AA to soy isolate. Soy protein concentrate had less AID and SID of Leu, Thr, Ala, and Asp than in potato protein ($P < 0.05$) and had less AID and SID of Asp compared to soy isolate ($P < 0.05$). The AID and SID of N and all AA was lowest in linseed meal among protein sources ($P < 0.05$).

## Discussion

As the availability of nutrient-rich feed ingredients, such as SBM, continues to decline, nutritionists must look towards the application of alternative feed ingredients with high utility in animal production. Common meals resulting from removal of oil from oilseeds include sunflower, cottonseed meal, and canola meals (Oil World, 2011) as well as camelina meal. Swine producers may also utilize animal and plant protein concentrates to satisfy the nutrient requirement of young and growing pigs (Schmidt et al., 2003). For many of the ingredients used in these experiments, the NRC (2012) profile of GE, N, and AA of ingredients were similar to values observed in the study. Differences were observed in potato protein concentrate, as the tested ingredient

revealed a CP content that was 87% the CP listed in the NRC (2012). This study also provides an AA profile of egg albumen, which is not presented in the NRC (2012).

The digestibility of N and AA in sunflower meal observed in this study agrees with previous reports, with the average SID of indispensable AA being 75% (NRC, 2012; Gonzalez-Vega and Stein, 2012). The digestibility of dispensable AA was observed to be lower than previously reported, which may be attributed to elevated fiber content, as CF content has a tendency to impact AA digestibility in the tested ingredients. With regards to replacing SBM in diets fed to pigs, sunflower contains less net energy and Lys content than SBM, and has resulted in decreased growth and lower carcass quality when compared to SBM in swine diets (Perez et al., 1986; Lipinski et al., 2002; Shelton et al., 2001; Defa et al., 2000). When fed with a Lys-supplemented diet, sunflower meal did not appear to have a negative impact on growth performance in you ng pigs (Akdag et al., 2008).

As cottonseeds are readily produced and available to animal producers in the United States, cottonseed meal is a possible protein source for swine, as the AA profile is similar to other common ingredients (Oil World, 2011; NRC, 2012). However, the digestibility of N and AA in cottonseed meal was observed to be much lower than other oilseed meals in this study, which agrees with previous reports (Gonzalez-Vega and Stein, 2012). Varying gossypol and fiber content may reduce the nutrient digestibility of cottonseed meal, as gossypol inhibits dehydrogenase enzymes and protein C activity (Lee et al., 1982). With a gossypol toxicity of 100 mg/kg, cottonseed meal with non-toxic levels has still revealed low feed efficiency and energy and AA digestibility when fed to growing pigs (Gonzalez-Vega and Stein, 2012). As gossypol levels was not

determined in this study, it appears that multiple factors may exist that reduce the nutrient digestibility of cottonseed meal.

Canola meal is a viable protein source for growing pigs, with N and AA digestibility similar to sunflower meal as seen in this study and previous reports (Gonzalez-Vega and Stein, 2012; NRC 2012) and has been shown to have similar growth response to SBM in diets fed to pigs (Keith and Bell, 1982). Fiber content of canola meal may be a limiting factor of its nutrient digestibility, as seen in the regression of CF and N and AA digestibility in this study. Though fiber components were not determined in this study, researchers have found that nutrient digestibility decreases as raffinose and stachyose concentrations increase in canola meal (Slominski, 1994).

Camelina meal was observed to have greater digestibility of many AA than cottonseed, but less digestibility than sunflower and canola meals. Others have reported similar AA digestibility between camelina and canola meals, with an average SID of 75% for essential AA (Almeida et al., 2013). With this study reporting the average SID of essential AA to be 65% for camelina meal, the difference may be due to fiber content and glucosinolates in the ingredient. Glucosinolates have been observed to decrease nutrient digestibility in pigs (Bohme et al., 1997; Gilani et al., 2005), however, were not determined in this study.. As cottonseed meal may contain gossypol and camelina meal often contains high levels of glucosinolates, these anti-nutritive factors may have also reduced the nutrient digestibility of cottonseed and camelina meals compared to the sunflower and canola meals.

For many years, animal proteins have served as a highly bioavailable and nutrient dense source of AA for young and growing pigs. Egg albumen is a fairly novel protein ingredient in the swine industry, and these experiments reveal it to have similar AA digestibility as blood meal and plasma meal and less AA digestibility than casein. Others have also reported similar AA digestibility between plasma meal and egg albumen (Schmidt et al., 2003). The nutrient digestibility of egg albumen remains unlisted in the NRC (2012), and these reports provide nutrient profiles and nutrient digestibility of a viable protein source for swine producers.

A by-product of pasteurized skim milk, casein is a highly digestible source of protein for growing pigs, as observed in this study, as well as weanling pigs (Cervantes-Pahm et al., 2010). Casein was revealed to have an average SID of AA of 95%, which was greater than the AA digestibility of egg albumen, blood meal, and plasma meal, and agrees with previous reports (Cervantes-Pahm et al., 2010; NRC, 2012). A reason for casein providing highly digestible AA may be due to its composition of phosphoproteins that are able to form gels in gastric solution, thereby increasing retention time of the protein and increasing digestion (Boirie et al., 1997).

A common protein supplement in swine diets, blood meal was shown to have an average SID of AA of 77%, which is supported by previous research (Almeida et al., 2013). However this is less than the predicted AA digestibility based on the NRC (2012), which lists the average SID of AA in blood meal to be 88%. It is possible that the processing of blood meal impacts the digestibility of the product. When blood meal is overheated during processing, amino acid digestibility has been observed to decrease,

and the meal appears to be a dark red color, as seen in the current study (Batterham et al., 1986).

Another by-product of animal production that serves as a viable source of amino acids is plasma meal (blood plasma). Plasma meal was observed to be as digestible as egg albumen in the current study, while being slightly more digestible than blood meal and less digestible than casein. This data agrees with previous reports that observed the amino acid digestibility to be 85% for many of the amino acids in plasma meal (Schmidt et al., 200; NRC, 2012). Others have also shown that plasma meal continues to be more digestible than blood meal in diets fed to pigs (Almeida et al., 2013). Among animal protein concentrates, it appears that the degree of processing may impact AA digestibility. Heating during blood meal processing may denature protein structure and reduce digestibility, which was observed to be less than other animal proteins in this study. Also, native protein characteristics of the ingredients can potentially affect nutrient digestibility. In this study, casein was the most readily digestible animal protein source, as this ingredient contains high levels of phosphoproteins, that may not be as present in the other ingredients.

Along with animal proteins, plant protein concentrates also serve as highly bioavailable ingredients that may be used in animal production. The N and AA digestibility of potato protein concentrate in the current study showed the average AA digestibility to be 95%, as this ingredient was the most readily digested plant protein concentrate tested in the study. This digestibility is higher than other researchers have observed (Smith et al., 1996; NRC, 2012), which may be due to our ingredient

containing less protease inhibitors that impede nutrient digestibility in pigs (Smith et al., 1996).

Concentrates derived from soybeans include soy protein concentrate and soy isolate. Though soy concentrate contains more crude fiber than soy isolate, the digestibility of the two ingredients appear to be very similar when fed to pigs (Li et al., 1991), which agrees with results in the current study. With soy concentrate containing little fiber, the difference in nutrient digestibility between ingredients due to fiber content is likely not significant as pigs are capable of extensive hindgut fermentation and have the capacity to digest fibrous components and free nutrients for absorption (NRC, 2012). The digestibility of Asp was the only difference observed between the ingredients, and the average AA digestibility was shown to be around 93%, which is fairly similar to previous reports (NRC, 2012; Li et al., 1991).

Linseed meal is another oilseed meal investigated in the current study and its nutrient digestibility was compared to plant concentrates. As would be assumed, the N and AA digestibility of linseed meal is much lower than plant concentrates, as the average AA digestibility nears 75%, which is similar to the few studies that have evaluated the AA digestibility of linseed meal (NRC, 2012). As linseed contains high levels of linolenic acid, linseed meal has been observed to increase linolenic acid deposition in the carcass of swine, revealing that linseed meal may be a proficient supplier of amino acids and fat for pigs (Enser et al., 2000).

Researchers have observed the existence of anti-nutritional factors in plant ingredients, and fiber content appears to impact the nutrient digestibility of ingredients when fed to livestock (Gonzalez-Vega and Stein, 2012; Slominski, 1994). Future work

determining the crude fiber and fibrous components of the experimental ingredients evaluated in the present study would provide researchers the ability to determine correlation between fiber and the nutrient digestibility of protein sources fed to swine.

In conclusion, sunflower and canola meals had greater AID and SID of AA compared to AA digestibility of cottonseed and camelina meal, and linseed meal appears to have similar digestibility values to canola meal. Cottonseed meal had the lowest N and AA digestibility among all ingredients. Among animal proteins, casein had greater AID and SID of AA than egg albumen, blood meal, and plasma meal, while those ingredients showed similar AA digestibility. The AID and SID of potato protein concentrate was greater than the AA digestibility of the other plant protein concentrates, soy concentrate and soy isolate, which revealed similar protein digestibility. With the exception of cottonseed meal, the experimental ingredients used in this study appear to be readily digestible in diets fed to growing pigs.

## References

Akdag, F., O. Elmaz, C. Kutay, and H. Demir. 2008. Effect of different diets on growth performance and feed efficiency in early weaned piglets. Turk. J. Vet. Anim. Sci., 32:7-11.

Almeida, F. N., J. K. Htoo, J. Thomson, and H. H. Stein. 2013. Amino acid digestibility in camelina products fed to growing pigs. Can. J. Anim. Sci. 93: 335–343.

Almeida, F. N., J. K. Htoo, J. Thomson and H. H. Stein. 2013 Comparative amino acid digestibility in US blood products fed to weanling pigs. Anim. Feed. Sci.and Tech. 181:1-4.

Batterham, E. S. R. F. Lowe, R. E. Darnell. 1986. Availability of lysine in meat meal, meat and bone meal and blood meal as determined by the slope-ratio assay with growing pigs, rats and chicks and by chemical techniques. Br. J. Nutr., 55: 427-440

Bohme, H., K. Aulrich, W. Schumann, K. Fischer. 1997. Studies on the suitability of false flax expeller as feedstuff. Feeding value and incorporation limits for pigs. Fett/Lipid 7: 254-259.

Chiba, L. I., 2001. Proteins supplements. In: A. J. Lewis and L. L. Southern (eds.) Swine nutrition (second edition). p 35. CRC Press LLC, Boca Raton London New York. Washington, D.C.

Boirie, Y., M. Dangin, P. Gachon, M. P. Vasson, J. L. Maubois, and B. Beaufrere. 1997. Slow and fast dietary proteins differently modulate postprandial protein accretion. Proc. Natl. Acad. Sci. U.S.A. 94:14930-5.

Cervantes-Pahm, S. K. and H. H. Stein. 2010. Ileal digestibility of amino acids in conventional, fermented, and enzyme-treated soybean meal and in soy protein isolate, fish meal, and casein fed to wenling pigs. J. Anim. Sci. 88:2674-2683.

Defa, L., G. F. Yi, S. Y. Qiao, C. T. Zheng, X. X. Xu, X. S. Piao, I. K. Han, and P. Thacker. 2000. Use of Chinese sunflower meal as a non-conventional protein feedstuff for growing-finishing pigs. Asian-Aust. J. Anim.Sci., 13: 666-672

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Defa, L., X. X. Xu, S. Y. Qiao, C. T. Zheng, Y. Chen, X. S. Piao, I. K. Han, and P. Thacker. 2000. Growth performance of growing-finishing pigs fed diets supplemented with Chinese cottonseed meal based on amino acid digestibilities. Asian-Aust. J. Anim.Sci., 13: 521-527.

Dilger, R. N., J. S. Sands, D. Ragland, and O. Adeola. 2004. Digestibility of nitrogen and amino acids in soybean meal with added soyhulls. J. Anim. Sci. 82:715-724.

Enser M., Richardson R. I., Wood J. D., Gill B. P., Sheard P. R. 2000. Feeding linseed to increase the n-3 PUFA of pork: Fatty acid composition of muscle, adipose tissue, liver and sausages. Meat Sci. 55:201–212.

Gilani, G. S., K. A. Cockell, and E. Sepehr. 2005. Effect of antinutritional factors on protein digestibility and amino acid availability in foods. J. AOAC Int. 88:967–987.

Gonzalez-Vega, J. C. and H. H. Stein. 2012. Amino acid digestibility of canola, cottonseed, and sunflower products fed to finishing pigs. J. Anim. Sci. 90:4391-4400.

Hansen, J. A., J. L. Nelssen, R. D. Goodband, and T. L. Weeden. 1993. Evaluation of animal protein supplements in diets for early-weaned pigs. J. Anim. Sci. 71:1853–1862.

Keith, M. O. and J. M. Bell. 1982. Effects of ammoniation on the composition and nutritional quality of low glucosinolate rapeseed (canola) meal. Can. J. Anim. Sci. 62:547-555.

Lee, C. Y. G., Y. S. Moon, J. H. Yuan, and A. F. Chen. Enzyme inactivation and inhibition by gossypol. Molecular and Cellular Biochemistry 47:65-70.

Li, D. F., J. L. Nelssen, P. G. Reddy, F. Blecha, R. D. Klemm, D. W. Giesting, J. D. Hancock, G. L. Allee, R. D. Goodband. 1991. Measuring suitability of soybean products for early-weaned pigs with immunological criteria. J. Anim. Sci. 69:3299–3307.

Lipinski, K., S. Bruzdzinski, J. Tywonczuk, and Z. Antoszkiewicz. 2002. Use of sunflower meal in the feeding of growing pigs. Annals Anim. Sci., Suppl. 2: 253-256.

Moon, H. K., J. W. Kim, K. N. Heo, Y. H. Kim, S. W. Kim, C. H. Kwon, I. S. Shin, and I. K. Han. 1994. Growth performance and amino acid digestibilities affected by various plant protein sources in growing-finishing pigs. Asian-Australas. J. Anim. Sci. 7:537–546.

Oil World, 2011. Major meals, World summary balances. Oil World Weekly, February 28, 2011,54: 95-104.

Perez, J. M., D. Bourdon, J. J. Baudet, and J. Evrard, 1986. Prediction of the energy value of sunflower meal from their cell wall contents. Journées Rech. Porc., 18: 35-46.

Schmidt, L. S., C. M. Nyachoti, and B. A. Slomiski. 2003. Nutritional evaluation of egg byproducts in diets for early-weaned pigs. J. Anim. Sci. 81:2270-2278.

Shelton, J. L., M. D. Hemann, R. M. Strode, G. L. Brashear, M. Ellis, F. K. McKeith,T. D. Bidner, and L. L. Southern. 2001. Effect of different protein sources on growth and carcass traits in growing-finishing pigs. J. Anim. Sci., 79: 2428-2435.

Slominski B. A., Campbell L. D., and Guenter W.. 1994. Carbohydrates and dietary fibre components of yellow and brown seeded canola. J. Agric. Food Chem. 42:704–707.

Smith, D. B., J. G. Roddick, J. L. Jones. 1996. Potato glycoalkaloids: some unanswered questions. Trends in Food Science and Technology 7: 126–131.

Smith, K. 1986. Advances in feeding soybean products. Pages 189–194 in Proc. World Conf. Emerging Technol. in the Fats and Oils Ind. A. R. Baldwin, ed. AOAC Press, Urbana, IL.

Tanksley Jr., T. D., 1990. Cottonseed meal. In: Thacker, P. A.; Kirkwood, R. N. (Ed.), Non-traditional feed sources for use in swine production: 139–151, Butterworth, Boston.

**Table 2.1 Ingredient composition of experimental diets, as-fed basis, for Exp. 1**

| Diet | Sunflower meal | Cottonseed meal | Canola Meal | Camelina meal | Nitrogen-Free |
|---|---|---|---|---|---|
| *Ingredients, g/kg* | | | | | |
| Sunflower meal | 523 | 0 | 0 | 0 | 0 |
| Cotton seed meal | 0 | 392 | 0 | 0 | 0 |
| Canola Meal | 0 | 0 | 420 | 0 | 0 |
| Camelina meal | 0 | 0 | 0 | 422 | 0 |
| Corn starch | 431 | 562 | 534 | 532 | 769 |
| Dextrose | 0 | 0 | 0 | 0 | 100 |
| Soy oil | 0 | 0 | 0 | 0 | 30 |
| Chromic oxide marker[1] | 25 | 25 | 25 | 25 | 25 |
| Monocalcium phosphate [2] | 15 | 15 | 15 | 15 | 20 |
| Limestone (38% Ca) [3] | 0 | 0 | 0 | 0 | 5 |
| Solka-floc | 0 | 0 | 0 | 0 | 40 |
| Salt | 3 | 3 | 3 | 3 | 3 |
| Vitamin premix [4] | 2 | 2 | 2 | 2 | 2 |
| Mineral premix [5] | 1 | 1 | 1 | 1 | 1 |
| Selenium premix [6] | 1 | 1 | 1 | 1 | 1 |
| Potassium carbonate | 0 | 0 | 0 | 0 | 4 |
| Magnessium oxide | 0 | 0 | 0 | 0 | 1 |
| Total | 1000 | 1000 | 1000 | 1000 | 1000 |

[1] 5 g Chromic oxide plus 20 g cornstarch
[2] 16% Ca, 21% P
[3] 38% Ca
[4] Vitamin premix contained per gram of premix: vitamin A, 2640 IU; vitamin $D_3$, 264 IU; vitamin E, 17.6 IU; vitamin K activity, 2.4 mg; menadione, 880 µg; vitamin $B_{12}$, 15.4 µg; riboflavin, 3.52 mg; D-pantothenic acid, 8.8 mg; niacin,13.2 mg.
[5] Mineral premix contained per gram of premix: Cu (as copper chloride), 9 mg; I (Ethylenediamine Dihydroiodide (EDDI)), 0.36 mg; Fe (as ferrous carbonate), 194 mg; Mn (as manganese oxide), 17 mg; and Zn (as zinc oxide), 149 mg
[6] Supplied 300 µg of Se per kilogram of diet

**Table 2.2 Ingredient composition of experimental diets, as-fed basis, for Exp. 2**

| Diets | **Egg Albumen** | **Casein** | **Blood Meal** | **Blood Plasma** | **Nitrogen-free** |
|---|---|---|---|---|---|
| *Ingredients, g/kg* | | | | | |
| Egg Albumen | 233 | 0 | 0 | 0 | 0 |
| Casein | 0 | 212 | 0 | 0 | 0 |
| Blood Meal | 0 | 0 | 213 | 0 | 0 |
| Blood Plasma | 0 | 0 | 0 | 243 | 0An |
| Corn Starch | 604 | 626 | 622 | 599 | 748 |
| Dextrose | 100 | 100 | 100 | 100 | 100 |
| Soy oil | 0 | 0 | 0 | 0 | 30 |
| Solka-floc | 0 | 0 | 0 | 0 | 50 |
| Chromic Oxide Prmx [1] | 25 | 25 | 25 | 25 | 25 |
| Monocalcium Phosphate [2] | 25 | 22 | 27 | 14 | 29 |
| Limestone (38% Ca)[3] | 6 | 8 | 7 | 12 | 6 |
| Salt | 4 | 4 | 4 | 4 | 4 |
| Vitamin Premix [4] | 2 | 2 | 2 | 2 | 2 |
| Mineral Premix [5] | 1 | 1 | 1 | 1 | 1 |
| Selenium Premix [6] | 1 | 1 | 1 | 1 | 1 |
| Potassium carbonate | 0 | 0 | 0 | 0 | 4 |
| Magnessium oxide | 0 | 0 | 0 | 0 | 1 |
| Total | 1000 | 1000 | 1000 | 1000 | 1000 |

[1] 5 g Chromic oxide plus 20 g cornstarch
[2] 16% Ca, 21% P
[3] 38% Ca
[4] Vitamin premix contained per gram of premix: vitamin A, 2640 IU; vitamin $D_3$, 264 IU; vitamin E, 17.6 IU; vitamin K activity, 2.4 mg; menadione, 880 μg; vitamin $B_{12}$, 15.4 μg; riboflavin, 3.52 mg; D-pantothenic acid, 8.8 mg; niacin,13.2 mg.
[5] Mineral premix contained per gram of premix: Cu (as copper chloride), 9 mg; I (Ethylenediamine Dihydroiodide (EDDI)), 0.36 mg; Fe (as ferrous carbonate), 194 mg; Mn (as manganese oxide), 17 mg; and Zn (as zinc oxide), 149 mg
[6] Supplied 300 μg of Se per kilogram of diet

**Table 2.3 Ingredient composition of experimental diets, as-fed basis, for Exp. 3**

| Diets | **Potato Protein** | **Soy Concentrate** | **Soy Isolate** | **Linseed Meal** | **Nitrogen-free** |
|---|---|---|---|---|---|
| *Ingredients, g/kg* | | | | | |
| Potato Protein Con. | 237 | 0 | 0 | 0 | 0 |
| Soy Protein Con. | 0 | 290 | 0 | 0 | 0 |
| Soy Protein Isolate | 0 | 0 | 223 | 0 | 0 |
| Linseed Meal | 0 | 0 | 0 | 568 | 0 |
| Corn Starch | 596 | 552 | 616 | 284 | 748 |
| Dextrose | 100 | 100 | 100 | 100 | 100 |
| Soy oil | 0 | 0 | 0 | 0 | 30 |
| Solka-floc | 0 | 0 | 0 | 0 | 50 |
| Chromic Oxide Prmx [1] | 25 | 25 | 25 | 25 | 25 |
| Monocalcium Phosphate [2] | 29 | 17 | 21 | 5 | 29 |
| Limestone [3] | 7 | 9 | 9 | 11 | 7 |
| Salt | 4 | 4 | 4 | 4 | 4 |
| Vitamin Premix [4] | 2 | 2 | 2 | 2 | 2 |
| Mineral Premix [5] | 1 | 1 | 1 | 1 | 1 |
| Selenium Premix [6] | 1 | 1 | 1 | 1 | 1 |
| Potassium carbonate | 0 | 0 | 0 | 0 | 4 |
| Magnessium oxide | 0 | 0 | 0 | 0 | 1 |
| Total | 1000 | 1000 | 1000 | 1000 | 1000 |

[1] 5 g Chromic oxide plus 20 g cornstarch
[2] 16% Ca, 21% P
[3] 38% Ca
[4] Vitamin premix contained per gram of premix: vitamin A, 2640 IU; vitamin $D_3$, 264 IU; vitamin E, 17.6 IU; vitamin K activity, 2.4 mg; menadione, 880 µg; vitamin $B_{12}$, 15.4 µg; riboflavin, 3.52 mg; D-pantothenic acid, 8.8 mg; niacin,13.2 mg.
[5] Mineral premix contained per gram of premix: Cu (as copper chloride), 9 mg; I (Ethylenediamine Dihydroiodide (EDDI)), 0.36 mg; Fe (as ferrous carbonate), 194 mg; Mn (as manganese oxide), 17 mg; and Zn (as zinc oxide), 149 mg
[6] Supplied 300 µg of Se per kilogram of diet

**Table 2.4 Analyzed composition of experimental diets for Exp. 1, as-fed basis**

| Diet | Sunflower meal | Cottonseed meal | Canola Meal | Camelina meal | Nitrogen-Free |
|---|---|---|---|---|---|
| GE, kcal / kg | 3742 | 3883 | 3859 | 3864 | 4055 |
| Protein, g/kg | 157 | 151 | 161 | 139 | 8 |
| Ca, g/kg | 5.5 | 3.8 | 7.2 | 4.2 | 5.0 |
| P, g/kg | 7.9 | 7.1 | 7.9 | 6.5 | 3.9 |
| Ca:P | 0.7 | 0.5 | 0.9 | 0.6 | 1.3 |
| | | | | | |
| Indispensable AA, g/kg | | | | | |
| Arg | 11.4 | 14.5 | 9.6 | 11.1 | 0.3 |
| His | 3.5 | 3.6 | 4.2 | 3.2 | 0.1 |
| Ile | 6.6 | 4.9 | 6.8 | 5.5 | 0.3 |
| Leu | 10.3 | 8.6 | 12.0 | 0.0 | 0.6 |
| Lys | 6.0 | 6.4 | 9.2 | 6.9 | 0.3 |
| Met | 3.1 | 2.1 | 3.2 | 2.4 | 0.0 |
| Phe | 7.4 | 7.6 | 7.0 | 6.0 | 0.3 |
| Thr | 5.8 | 4.6 | 7.0 | 5.7 | 0.2 |
| Trp | 1.7 | 1.3 | 2.0 | 2.1 | <0.4 |
| Val | 7.9 | 6.4 | 8.5 | 7.3 | 0.3 |
| Dispensable AA, g/kg | | | | | |
| Ala | 6.8 | 5.8 | 7.4 | 6.4 | 0.4 |
| Asp | 14.0 | 12.6 | 11.7 | 11.8 | 0.5 |
| Cys | 2.4 | 2.1 | 3.8 | 2.9 | 0.1 |
| Glu | 29.2 | 26.9 | 29.2 | 23.8 | 1.0 |
| Gly | 8.9 | 6.0 | 8.4 | 7.3 | 0.3 |
| Pro | 7.2 | 6.2 | 10.6 | 7.9 | 0.6 |
| Ser | 6.1 | 5.6 | 6.4 | 6.0 | 0.3 |
| Tyr | 3.7 | 4.0 | 4.5 | 3.5 | 0.2 |
| Total | 143.4 | 130.3 | 153.6 | 131.3 | 6.0 |

**Table 2.5 Analyzed composition of ingredients for Exp. 1, as-fed basis**

| Item | **Sunflower meal** | **Cottonseed meal** | **Canola Meal** | **Camelina meal** |
|---|---|---|---|---|
| DM, g/kg | 922 | 916 | 912 | 911 |
| Protein, g/kg | 32 | 42 | 39 | 35 |
| GE, kcal / kg | 4287 | 4352 | 4241 | 4757 |
| Ca, g/kg | 4.7 | 2.6 | 6.9 | 3.2 |
| P, g/kg | 9.6 | 11.4 | 8.7 | 8.1 |
| | | | | |
| Indispensable AA, g/kg | | | | |
| Arg | 23.1 | 45.2 | 22.5 | 28.2 |
| His | 7.2 | 11.0 | 9.7 | 7.7 |
| Ile | 13.4 | 14.0 | 15.7 | 13.3 |
| Leu | 21.0 | 25.2 | 27.5 | 23.0 |
| Lys | 12.5 | 19.3 | 21.6 | 16.9 |
| Met | 6.5 | 6.7 | 7.4 | 6.0 |
| Phe | 14.9 | 21.8 | 16.1 | 14.4 |
| Thr | 11.7 | 14.0 | 16.2 | 14.1 |
| Trp | 3.5 | 3.0 | 4.7 | 4.9 |
| Val | 15.8 | 19.4 | 19.8 | 18.0 |
| Dispensable AA, g/kg | | | | |
| Ala | 13.7 | 16.9 | 16.7 | 15.1 |
| Asp | 28.2 | 38.0 | 26.7 | 28.8 |
| Cys | 4.8 | 6.6 | 8.6 | 7.0 |
| Glu | 58.0 | 80.6 | 65.5 | 56.2 |
| Gly | 17.9 | 17.7 | 19.3 | 17.7 |
| Pro | 14.3 | 16.3 | 24.1 | 18.6 |
| Ser | 12.2 | 17.6 | 14.3 | 14.4 |
| Tyr | 7.6 | 11.5 | 11.0 | 9.4 |
| Total | 288.4 | 386.3 | 352.3 | 317.7 |

**Table 2.6 Analyzed composition of experimental diets for Exp, 2, as-fed basis**

| Diet | Egg Albumen | Casein | Blood Meal | Blood Plasma | Nitrogen-free |
|---|---|---|---|---|---|
| GE, kcal / kg | 3490 | 3742 | 3608 | 3770 | 3810 |
| Protein, g/kg | 217 | 191 | 206 | 193 | 5 |
| Ca, g/kg | 6.8 | 7.2 | 6.7 | 6.9 | 7.1 |
| P, g/kg | 6.1 | 6.1 | 5.8 | 6.3 | 5.9 |
| Ca:P | 1.1 | 1.2 | 1.2 | 1.1 | 1.2 |
| | | | | | |
| Indispensable AA, g/kg | | | | | |
| Arg | 11.5 | 5.9 | 9.5 | 11.4 | 0.2 |
| His | 5.0 | 5.7 | 13.6 | 6.2 | 4.0 |
| Ile | 10.5 | 10.8 | 2.7 | 6.0 | 0.2 |
| Leu | 16.8 | 18.6 | 24.3 | 18.4 | 0.4 |
| Lys | 13.9 | 15.2 | 16.6 | 17.8 | 0.2 |
| Met | 7.2 | 6.0 | 1.6 | 2.3 | 0.1 |
| Phe | 12.2 | 9.8 | 12.3 | 10.4 | 0.3 |
| Thr | 8.9 | 8.6 | 7.2 | 12.7 | 0.1 |
| Trp | 3.3 | 2.7 | 2.5 | 3.9 | 0.4 |
| Val | 13.8 | 13.0 | 16.1 | 13.3 | 0.2 |
| Dispensable AA, g/kg | | | | | |
| Ala | 12.4 | 5.8 | 14.5 | 10.1 | 0.3 |
| Asp | 21.0 | 13.3 | 21.7 | 19.7 | 0.3 |
| Cys | 5.2 | 0.7 | 2.7 | 5.9 | 0.1 |
| Glu | 26.0 | 42.7 | 19.2 | 26.5 | 0.5 |
| Gly | 7.1 | 3.6 | 9.4 | 6.8 | 0.2 |
| Pro | 7.1 | 23.0 | 8.5 | 10.2 | 0.2 |
| Ser | 11.7 | 9.1 | 8.6 | 11.1 | 0.2 |
| Tyr | 7.6 | 10.5 | 5.8 | 9.7 | 0.2 |
| Total | 201.7 | 205.2 | 197.2 | 203.1 | 8.4 |

**Table 2.7 Analyzed composition of ingredients for Exp. 2, as-fed basis**

| Item | Egg Albumen | Casein | Blood Meal | Blood Plasma |
|---|---|---|---|---|
| DM, g/kg | 949 | 913 | 919 | 938 |
| Protein, g/kg | 808 | 894 | 914 | 784 |
| GE, kcal / kg | 6280 | 5680 | 5315 | 4748 |
| Ca, g/kg | 2.8 | 2.1 | 0.6 | 1.4 |
| P, g/kg | 6.8 | 6.8 | 2.2 | 12.6 |
| | | | | |
| Indispensable AA, g/kg | | | | |
| Arg | 49.5 | 27.8 | 44.8 | 46.9 |
| His | 21.3 | 26.7 | 63.7 | 25.6 |
| Ile | 45.2 | 51.1 | 12.5 | 24.5 |
| Leu | 72.3 | 87.8 | 114.2 | 75.6 |
| Lys | 59.8 | 71.9 | 78.1 | 73.3 |
| Met | 31.0 | 28.3 | 7.6 | 9.5 |
| Phe | 52.4 | 46.4 | 57.9 | 42.6 |
| Thr | 38.2 | 40.8 | 33.7 | 52.1 |
| Trp | 14.3 | 12.8 | 11.8 | 16.1 |
| Val | 59.4 | 61.1 | 75.5 | 54.8 |
| Dispensable AA, g/kg | | | | |
| Ala | 53.1 | 27.4 | 67.9 | 41.7 |
| Asp | 90.0 | 62.6 | 102.0 | 81.0 |
| Cys | 22.3 | 3.4 | 12.8 | 24.3 |
| Glu | 111.6 | 201.4 | 90.2 | 108.9 |
| Gly | 30.3 | 16.8 | 43.9 | 27.9 |
| Pro | 30.5 | 108.5 | 39.8 | 41.9 |
| Ser | 50.0 | 42.7 | 40.6 | 45.7 |
| Tyr | 32.7 | 49.5 | 27.0 | 40.1 |
| Total | 865.7 | 968.1 | 925.9 | 835.9 |

**Table 2.8 Analyzed composition of experimental diets for Exp, 3, as-fed basis**

| Diet | Potato Protein | Soy Concentrate | Soy Isolate | Linseed Meal | Nitrogen-free |
|---|---|---|---|---|---|
| GE, kcal / kg | 3624 | 3700 | 3649 | 3112 | 3805 |
| Protein, g/kg | 190 | 189 | 199 | 220 | 3 |
| Ca, g/kg | 6.8 | 7.2 | 6.7 | 6.7 | 7.1 |
| P, g/kg | 6.1 | 5.8 | 6.2 | 6.4 | 6.1 |
| Ca:P | 1.1 | 1.2 | 1.1 | 1.0 | 1.2 |
| | | | | | |
| Indispensable AA, g/kg | | | | | |
| Arg | 10.0 | 13.2 | 14.1 | 20.3 | 0.1 |
| His | 4.6 | 5.1 | 5.3 | 4.6 | 2.0 |
| Ile | 11.6 | 9.0 | 3.3 | 9.7 | 0.1 |
| Leu | 21.1 | 16.7 | 15.4 | 13.6 | 0.4 |
| Lys | 16.0 | 11.9 | 11.8 | 8.7 | 0.2 |
| Met | 4.5 | 2.6 | 2.4 | 4.0 | 0.1 |
| Phe | 13.2 | 9.8 | 10.2 | 10.7 | 0.1 |
| Thr | 11.7 | 7.2 | 6.7 | 7.6 | 0.2 |
| Trp | 2.4 | 2.4 | 2.6 | 3.5 | 0.2 |
| Val | 2.8 | 2.5 | 2.2 | 3.6 | 0.1 |
| Dispensable AA, g/kg | | | | | |
| Ala | 10.2 | 8.5 | 8.5 | 10.3 | 0.2 |
| Asp | 24.5 | 21.1 | 22.3 | 20.1 | 0.2 |
| Cys | 2.9 | 2.8 | 2.2 | 3.7 | 0.1 |
| Glu | 21.2 | 33.1 | 36.3 | 42.8 | 0.3 |
| Gly | 9.8 | 7.8 | 7.9 | 12.8 | 0.3 |
| Pro | 9.9 | 9.3 | 9.7 | 7.9 | 0.2 |
| Ser | 9.4 | 7.9 | 8.2 | 8.4 | 0.2 |
| Tyr | 10.9 | 6.6 | 6.4 | 5.6 | 0.2 |
| Total | 210.0 | 184.7 | 189.8 | 210.1 | 7.6 |

**Table 2.9 Analyzed composition of ingredients for Exp. 3, as-fed basis**

| Item | Potato Protein | Soy Concentrate | Soy Isolate | Linseed Meal |
|---|---|---|---|---|
| DM, g/kg | 943 | 935 | 937 | 929 |
| Protein, g/kg | 695 | 643 | 696 | 391 |
| GE, kcal / kg | 5259 | 4645 | 5279 | 5956 |
| Ca, g/kg | 2.8 | 3.0 | 1.8 | 3.6 |
| P, g/kg | 7.6 | 8.1 | 7.3 | 8.5 |
| | | | | |
| Indispensable AA, g/kg | | | | |
| Arg | 42.1 | 45.8 | 63.2 | 35.8 |
| His | 19.5 | 17.6 | 22.5 | 8.8 |
| Ile | 49.5 | 31.1 | 41.5 | 16.9 |
| Leu | 89.1 | 50.5 | 67.3 | 23.0 |
| Lys | 67.8 | 41.0 | 52.6 | 15.2 |
| Met | 18.9 | 9.1 | 10.9 | 6.9 |
| Phe | 55.6 | 33.1 | 45.4 | 18.8 |
| Thr | 49.6 | 24.9 | 31.3 | 13.7 |
| Trp | 10.4 | 8.1 | 11.5 | 6.0 |
| Val | 11.7 | 8.9 | 9.9 | 6.4 |
| Dispensable AA, g/kg | | | | |
| Ala | 43.0 | 29.3 | 38.0 | 18.1 |
| Asp | 104.2 | 72.8 | 98.7 | 35.8 |
| Cys | 11.7 | 8.9 | 9.9 | 6.4 |
| Glu | 89.2 | 114.9 | 163.5 | 76.0 |
| Gly | 40.9 | 27.2 | 35.0 | 22.4 |
| Pro | 42.1 | 31.8 | 43.8 | 13.9 |
| Ser | 38.9 | 27.4 | 36.7 | 15.1 |
| Tyr | 46.1 | 22.4 | 29.6 | 9.8 |
| Total | 878.6 | 629.9 | 845.8 | 366.4 |

**Table 2.10 Endogenous nutrient losses (mg/kg of DMI) of nitrogen and amino acids at the terminal ileum[a] for Exp. 1**

| | | Range[b] | | |
|---|---|---|---|---|
| Item | Average | min | max | SD |
| Nitrogen | 3324 | 2595 | 4533 | 872 |
| Indispensable AA | | | | |
| Arg | 794 | 565 | 1243 | 270 |
| His | 220 | 172 | 303 | 51 |
| Ile | 442 | 344 | 605 | 98 |
| Leu | 726 | 574 | 1002 | 167 |
| Lys | 719 | 596 | 813 | 87 |
| Met | 103 | 80 | 151 | 28 |
| Phe | 454 | 401 | 586 | 75 |
| Thr | 732 | 631 | 946 | 125 |
| Trp | 169 | 126 | 208 | 30 |
| Val | 827 | 669 | 1078 | 169 |
| Dispensable AA | | | | |
| Ala | 796 | 619 | 1017 | 198 |
| Asp | 1039 | 827 | 1362 | 224 |
| Cys | 216 | 172 | 284 | 42 |
| Glu | 1233 | 975 | 1645 | 269 |
| Gly | 1966 | 1456 | 2922 | 613 |
| Pro | 6556 | 4305 | 11735 | 3010 |
| Ser | 729 | 604 | 870 | 123 |
| Tyr | 370 | 264 | 511 | 89 |
| Total | 18281 | 14380 | 25472 | 4769 |

**[a]n = 8 pigs**
**[b]Minimum to maximum**

**Table 2.11 Endogenous nutrient losses (mg/kg of DMI) of nitrogen and amino acids at the terminal ileum[a] for Exp. 2**

| | | Range[b] | | |
|---|---|---|---|---|
| Item | Average | min | max | SD |
| Nitrogen | 3073 | 2165 | 4030 | 604 |
| Indispensable AA | | | | |
| Arg | 723 | 598 | 904 | 89 |
| His | 313 | 214 | 408 | 67 |
| Ile | 464 | 304 | 700 | 129 |
| Leu | 877 | 564 | 1225 | 219 |
| Lys | 774 | 507 | 1035 | 189 |
| Met | 124 | 68 | 210 | 55 |
| Phe | 540 | 350 | 744 | 140 |
| Thr | 820 | 575 | 1196 | 200 |
| Trp | 195 | 124 | 321 | 64 |
| Val | 664 | 451 | 992 | 176 |
| Dispensable AA | | | | |
| Ala | 743 | 564 | 992 | 129 |
| Asp | 1130 | 778 | 1604 | 269 |
| Cys | 272 | 192 | 394 | 66 |
| Glu | 1332 | 879 | 1867 | 318 |
| Gly | 1474 | 1094 | 1977 | 303 |
| Pro | 3856 | 1441 | 5325 | 1363 |
| Ser | 754 | 566 | 1123 | 196 |
| Tyr | 371 | 267 | 490 | 93 |
| Total | 15573 | 11748 | 19106 | 2168 |

**[a]n = 8 pigs**
**[b]Minimum to maximum**

**Table 2.12 Endogenous nutrient losses (mg/kg of DMI) of nitrogen and amino acids at the terminal ileum[a] for Exp. 3**

| | | Range[b] | | |
|---|---|---|---|---|
| Item | Average | min | max | SD |
| Nitrogen | 1957 | 1487 | 2388 | 347 |
| Indispensable AA | | | | |
| Arg | 450 | 357 | 577 | 92 |
| His | 239 | 123 | 625 | 159 |
| Ile | 265 | 164 | 372 | 65 |
| Leu | 477 | 327 | 640 | 101 |
| Lys | 376 | 15 | 515 | 161 |
| Met | 61 | 41 | 104 | 22 |
| Phe | 302 | 205 | 387 | 59 |
| Thr | 466 | 338 | 586 | 89 |
| Trp | 111 | 72 | 144 | 25 |
| Val | 371 | 256 | 476 | 74 |
| Dispensable AA | | | | |
| Ala | 481 | 348 | 551 | 74 |
| Asp | 704 | 470 | 952 | 151 |
| Cys | 147 | 113 | 193 | 27 |
| Glu | 802 | 522 | 1056 | 168 |
| Gly | 1184 | 839 | 1581 | 294 |
| Pro | 3975 | 818 | 6644 | 1899 |
| Ser | 452 | 286 | 573 | 94 |
| Tyr | 219 | 133 | 253 | 40 |
| Total | 11231 | 8223 | 14100 | 2334 |

**[a]n = 8 pigs**
**[b]Minimum to maximum**

**Table 2.13 Apparent ileal digestibility of N and AA in experimental ingredients for Exp. 1[1]**

| Items | Sunflower meal | Cottonseed meal | Canola Meal | Camelina meal | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen, % | 65.7[a] | 50.8[bc] | 59.9[ab] | 49.6[c] | 2.94 | 0.0007 |
| Indispensable AA, % | | | | | | |
| Arg | 84.4[a] | 76.4[b] | 77.9[b] | 76.9[b] | 1.23 | 0.0004 |
| His | 73.2[a] | 58.8[c] | 76.3[a] | 65.5[b] | 2.09 | <.0001 |
| Ile | 70.7[a] | 40.1[c] | 67.3[a] | 54.8[b] | 2.32 | <.0001 |
| Leu | 71.0[a] | 41.9[c] | 70.9[a] | 59.3[b] | 2.38 | <.0001 |
| Lys | 57.9[a] | 23.9[c] | 60.5[a] | 43.3[b] | 4.53 | <.0001 |
| Met | 80.0[a] | 41.1[c] | 77.8[a] | 66.6[b] | 2.75 | <.0001 |
| Phe | 74.2[a] | 60.1[b] | 70.9[a] | 60.4[b] | 1.87 | <.0001 |
| Thr | 61.3[a] | 25.6[c] | 57.7[a] | 38.1[b] | 3.26 | <.0001 |
| Trp | 72.3 | 68.8 | 75.3 | 71.8 | 2.58 | 0.1409 |
| Val | 66.2[a] | 34.4[c] | 61.3[a] | 49.9[b] | 2.80 | <.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 65.9[a] | 37.8[c] | 64.6[a] | 48.2[b] | 2.65 | <.0001 |
| Asp | 67.1[a] | 50.1[b] | 58.8[ab] | 55.8[b] | 2.42 | 0.0005 |
| Cys | 56.9[a] | 40.0[b] | 63.2[a] | 42.0[b] | 3.76 | <.0001 |
| Glu | 81.4[a] | 69.0[b] | 79.2[a] | 70.6[b] | 1.62 | <.0001 |
| Gly | 47[ab] | 30.3[c] | 52.6[a] | 35.3[bc] | 6.22 | 0.0009 |
| Pro | 43.6 | 26.0 | 48.7 | 46.4 | 8.27 | 0.1735 |
| Ser | 62.7[a] | 42.9[b] | 60.3[a] | 46.3[b] | 2.78 | <.0001 |
| Tyr | 68.6[a] | 53.4[b] | 66.8[a] | 44.2[c] | 2.46 | <.0001 |
| Mean | 69.2[a] | 50.8[b] | 66.3[a] | 55.9[b] | 2.18 | <.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 2.14 Standardized ileal digestibility of N and AA in experimental ingredients for Exp. 1[1]**

| Items | Sunflower meal | Cottonseed meal | Canola Meal | Camelina meal | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen, % | 78.2[a] | 63.3[bc] | 72.4[ab] | 62.1[c] | 2.94 | 0.0007 |
| Indispensable AA, % | | | | | | |
| Arg | 90.6[a] | 82.6[b] | 84.2[b] | 83.2[b] | 1.23 | 0.0004 |
| His | 78.7[a] | 64.3[c] | 81.8[a] | 71.1[b] | 2.09 | <.0001 |
| Ile | 77.5[a] | 46.9[c] | 74.1[a] | 61.6[b] | 2.32 | <.0001 |
| Leu | 77.6[a] | 48.5[c] | 77.5[a] | 65.9[b] | 2.38 | <.0001 |
| Lys | 67.1[a] | 33.1[c] | 69.7[a] | 52.5[b] | 4.53 | <.0001 |
| Met | 83.5[a] | 44.6[c] | 81.3[a] | 70.1[b] | 2.75 | <.0001 |
| Phe | 80.1[a] | 66.1[b] | 76.8[a] | 66.3[b] | 1.87 | <.0001 |
| Thr | 72.9[a] | 37.2[c] | 69.3[a] | 49.6[b] | 3.26 | <.0001 |
| Trp | 81.0 | 77.5 | 84.0 | 80.5 | 2.58 | 0.1409 |
| Val | 76.2[a] | 44.4[c] | 71.3[a] | 59.9[b] | 2.80 | <.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 76.9[a] | 48.8[c] | 75.6[a] | 59.3[b] | 2.65 | <.0001 |
| Asp | 74.7[a] | 57.7[b] | 66.4[ab] | 63.4[b] | 2.42 | 0.0005 |
| Cys | 63.9[a] | 47.0[b] | 70.2[a] | 49.1[b] | 3.76 | <.0001 |
| Glu | 85.5[a] | 73.1[b] | 83.3[a] | 74.8[b] | 1.62 | <.0001 |
| Gly | 70.9[a] | 53.8[b] | 76.0[a] | 58.7[b] | 6.22 | 0.0009 |
| Pro | 118.6 | 101.0 | 123.7 | 121.5 | 8.27 | 0.1735 |
| Ser | 73.8[a] | 54.0[b] | 71.3[a] | 57.4[b] | 2.78 | <.0001 |
| Tyr | 77.2[a] | 62.0[b] | 75.4[a] | 52.8[c] | 2.46 | <.0001 |
| Mean | 81.1[a] | 62.7[b] | 78.2[a] | 67.8[b] | 2.18 | <.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 2.15 Apparent ileal digestibility of N and AA in experimental ingredients for Exp. 2[1]**

| Items | Egg Albumen | Casein | Blood Meal | Plasma Meal | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen, % | 79.2[b] | 91.5[a] | 74.7[b] | 76.2[b] | 1.82 | <.0001 |
| Indispensable AA, % | | | | | | |
| Arg | 82.3[b] | 90.7[a] | 75.8[c] | 84.6[b] | 2.06 | <.0001 |
| His | 79.6[c] | 94.3[a] | 88.1[b] | 81.7[c] | 1.77 | <.0001 |
| Ile | 79.8[b] | 94.6[a] | 57.4[c] | 76.2[b] | 2.03 | <.0001 |
| Leu | 79.3[b] | 95.2[a] | 85.3[b] | 82.0[b] | 1.96 | <.0001 |
| Lys | 80.4[b] | 94.3[a] | 84.8[b] | 80.8[b] | 1.69 | <.0001 |
| Met | 81.1[b] | 97.2[a] | 80.8[b] | 80.2[b] | 1.89 | <.0001 |
| Phe | 79.2[b] | 94.8[a] | 85.9[b] | 82.0[b] | 1.83 | <.0001 |
| Thr | 79.8[b] | 88.8[a] | 67.7[c] | 76.5[b] | 1.97 | <.0001 |
| Trp | 79.2[b] | 92.5[a] | 81.2[b] | 81.9[b] | 2.36 | <.0001 |
| Val | 79.9[b] | 94.2[a] | 83.3[b] | 80.4[b] | 1.87 | <.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 81.6[ab] | 87.4[a] | 84.2[ab] | 78.7[b] | 2.04 | <.0001 |
| Asp | 80.4[b] | 90.6[a] | 79.0[b] | 78.2[b] | 1.86 | <.0001 |
| Cys | 83.3[a] | 66.7[b] | 34.0[c] | 83.0[a] | 3.76 | <.0001 |
| Glu | 79.6[b] | 95.4[a] | 75.6[b] | 79.0[b] | 1.83 | <.0001 |
| Gly | 79.2 | 74.6 | 71.9 | 63.3 | 6.29 | <.0001 |
| Pro | 97.5[a] | 117.0[a] | 59.6[b] | 96.7[a] | 13.48 | 0.0012 |
| Ser | 78.1[b] | 92.3[a] | 69.6[c] | 76.2[bc] | 3.06 | <.0001 |
| Tyr | 80.5[b] | 95.9[a] | 80.0[b] | 83.2[b] | 1.83 | <.0001 |
| Mean | 80.2[b] | 93.2[a] | 76.9[b] | 78.8[b] | 1.79 | <.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 2.16 Standardized ileal digestibility of N and AA in experimental ingredients for Exp. 2[1]**

| Items | Egg Albumen | Casein | Blood Meal | Plasma Meal | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen, % | 81.3[b] | 93.7[a] | 76.9[b] | 78.3[b] | 1.82 | <.0001 |
| Indispensable AA, % | | | | | | |
| Arg | 83.7[b] | 92.0[a] | 77.1[c] | 86.0[b] | 2.06 | <.0001 |
| His | 81.0[c] | 95.7[a] | 89.4[b] | 83.1[c] | 1.77 | <.0001 |
| Ile | 80.7[b] | 95.5[a] | 58.4[c] | 77.2[b] | 2.03 | <.0001 |
| Leu | 80.5[b] | 96.4[a] | 86.4[b] | 83.1[b] | 1.96 | <.0001 |
| Lys | 81.6[b] | 95.5[a] | 86.0[b] | 82.0[b] | 1.69 | <.0001 |
| Met | 81.5[b] | 97.6[a] | 81.2[b] | 80.6[b] | 1.89 | <.0001 |
| Phe | 81.2[b] | 95.7[a] | 86.9[b] | 82.9[a] | 1.83 | <.0001 |
| Thr | 80.8[b] | 90.8[a] | 69.7[c] | 78.5[b] | 1.97 | <.0001 |
| Trp | 80.5[b] | 93.7[a] | 82.4[b] | 83.1[b] | 2.35 | <.0001 |
| Val | 81.0[b] | 95.3[a] | 84.4[b] | 81.5[b] | 1.87 | <.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 82.9[ab] | 88.7[a] | 85.5[ab] | 80.0[b] | 2.04 | <.0001 |
| Asp | 81.5[b] | 91.7[a] | 80.2[b] | 79.4[a] | 1.86 | <.0001 |
| Cys | 84.4[a] | 67.9[b] | 35.1[c] | 84.2[a] | 3.76 | <.0001 |
| Glu | 80.7[b] | 96.5[a] | 76.7[b] | 80.1[b] | 1.83 | <.0001 |
| Gly | 83.7 | 79.1 | 76.4 | 67.8 | 6.29 | <.0001 |
| Pro | 109.1[a] | 128.7[a] | 71.2[b] | 108.4[a] | 13.48 | 0.0002 |
| Ser | 79.5[b] | 93.7[a] | 70.9[c] | 77.6[bc] | 3.06 | <.0001 |
| Tyr | 81.6[b] | 97.0[a] | 81.0[b] | 84.3[b] | 1.83 | <.0001 |
| Mean | 81.8[b] | 94.9[a] | 78.6[b] | 80.4[b] | 1.79 | <.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 2.17 Apparent ileal digestibility of N and AA in experimental ingredients for Exp. 3[1]**

| Items | Potato Protein | Soy Concentrate | Soy Isolate | Linseed Meal | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen, % | 85.7[a] | 85.3[a] | 87.8[a] | 68.7[b] | 1.27 | <.0001 |
| Indispensable AA, % | | | | | | |
| Arg | 90.8[a] | 93.0[a] | 94.4[a] | 80.0[b] | 0.95 | <.0001 |
| His | 90.1[a] | 90.3[a] | 90.0[a] | 69.4[b] | 3.04 | <.0001 |
| Ile | 90.9[a] | 88.0[a] | 89.5[a] | 75.1[b] | 0.97 | <.0001 |
| Leu | 92.2[a] | 87.9[b] | 89.2[ab] | 74.4[c] | 1.03 | <.0001 |
| Lys | 92.5[a] | 90.1[a] | 93.9[a] | 64.3[b] | 2.58 | <.0001 |
| Met | 92.8[a] | 89.6[a] | 89.4[a] | 80.9[b] | 0.96 | <.0001 |
| Phe | 91.7[a] | 88.9[a] | 90.5[a] | 76.7[b] | 0.90 | <.0001 |
| Thr | 86.9[a] | 80.5[b] | 80.8[b] | 64.7[c] | 1.52 | <.0001 |
| Trp | 89.8[a] | 88.2[a] | 90.4[a] | 81.2[b] | 1.32 | <.0001 |
| Val | 90.0[a] | 86.1[a] | 87.4[a] | 73.8[b] | 1.11 | <.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 88.2[a] | 82.8[b] | 84.3[ab] | 71.7[c] | 1.35 | <.0001 |
| Asp | 88.8[a] | 82.1[b] | 89.0[a] | 72.4[c] | 1.29 | <.0001 |
| Cys | 74.1[a] | 76.2[a] | 78.3[a] | 59.2[b] | 2.21 | <.0001 |
| Glu | 89.5[a] | 89.7[a] | 93.2[a] | 78.9[b] | 1.04 | <.0001 |
| Gly | 83.4[a] | 77.1[a] | 80.2[a] | 63.6[b] | 1.92 | <.0001 |
| Pro | 82.4[a] | 78.6[a] | 81.2[a] | 63.4[b] | 3.06 | <.0001 |
| Ser | 84.6[a] | 86.2[a] | 87.1[a] | 69.3[b] | 1.16 | <.0001 |
| Tyr | 91.0[a] | 88.4[a] | 89.0[a] | 71.7[b] | 1.26 | <.0001 |
| Mean | 88.7[a] | 85.7[a] | 88.8[a] | 72.5[b] | 1.14 | <.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 2.18 Standardized ileal digestibility of N and AA in experimental ingredients for Exp. 3[1]**

| Items | Potato Protein | Soy Concentrate | Soy Isolate | Linseed Meal | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen, % | 93.0[a] | 92.6[a] | 95.1[a] | 76.1[b] | 1.27 | <.0001 |
| Indispensable AA, % | | | | | | |
| Arg | 94.3[a] | 96.5[a] | 98.0[a] | 83.6[b] | 0.95 | <.0001 |
| His | 96.0[a] | 96.2[a] | 96.0[a] | 75.3[b] | 3.04 | <.0001 |
| Ile | 94.4[a] | 91.5[a] | 93.0[a] | 78.6[b] | 0.97 | <.0001 |
| Leu | 96.3[a] | 91.9[b] | 93.2[ab] | 78.5[c] | 1.02 | <.0001 |
| Lys | 96.8[a] | 94.4[a] | 98.1[a] | 68.6[b] | 2.58 | <.0001 |
| Met | 95.3[a] | 92.2[a] | 92.0[a] | 83.4[b] | 0.96 | <.0001 |
| Phe | 95.3[a] | 92.6[a] | 94.1[a] | 80.4[b] | 0.90 | <.0001 |
| Thr | 94.7[a] | 88.3[b] | 88.6[b] | 72.5[c] | 1.52 | <.0001 |
| Trp | 94.4[a] | 92.9[a] | 95.0[a] | 85.9[b] | 1.32 | <.0001 |
| Val | 94.5[a] | 90.6[a] | 91.9[a] | 78.3[b] | 1.11 | <.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 94.8[a] | 89.4[b] | 90.9[ab] | 78.3[c] | 1.35 | <.0001 |
| Asp | 92.8[a] | 86.1[b] | 93.1[a] | 76.4[c] | 1.29 | <.0001 |
| Cys | 80.6[a] | 82.8[a] | 84.9[a] | 65.7[b] | 2.21 | <.0001 |
| Glu | 92.0[a] | 92.2[a] | 95.7[a] | 81.4[b] | 1.04 | <.0001 |
| Gly | 98.5[a] | 92.2[a] | 95.2[a] | 78.7[b] | 1.92 | <.0001 |
| Pro | 133.7[a] | 126.2[ab] | 132.8[a] | 114.9[b] | 5.36 | <.0001 |
| Ser | 91.0[a] | 92.6[a] | 93.5[a] | 75.7[b] | 1.16 | <.0001 |
| Tyr | 95.8[a] | 93.2[a] | 93.8[a] | 76.5[a] | 1.26 | <.0001 |
| Mean | 95.8[a] | 92.7[a] | 95.9[a] | 79.6[b] | 1.14 | <.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

# CHAPTER 3.
# DETERMINING THE IMPACT OF DIETARY FIBER ON ENERGY, NITROGEN, AND AMINO ACID DIGESTIBILITY OF SOYBEAN MEAL FED TO GROWING PIGS


## Abstract

Two experiments were conducted to determine the impact that different types of fiber have on the energy, nitrogen (N), and amino acid (AA) digestibility of soybean meal fed to growing pigs. In both studies, soybean meal served as the predominant form of amino acids for the animals, as the fibrous ingredients added little protein to the semi-purified, corn-starch based diets. A semi-purified, nitrogen-free diet (NFD) was used to estimate endogenous flow of AA. Pigs were surgically fitted with a simple T-cannula at the distal ileum and fed 4 experimental diets and the NFD on a 5 × 2 crossover arrangement in a randomized crossover design, with 5 diets and 2 periods. For experiment 1 (Exp. 1), soybean meal (SBM), SBM + corn hulls, SBM + rice hulls, and SBM + wheat straw were fed to 19 45-kg barrows to determine apparent (AID) and standardized ileal digestibility (SID) of N and AA at the terminal ileum, apparent total tract digestibility (ATTD) of energy and N, and apparent hindgut digestibility (AHD) of energy and N. Rice hulls reduced the AID and SID of N, Arg, Ile, Thr, Trp, and Cys compared with the control and corn fiber diet and had lower AID of N and Glu and SID of N and Leu compared with the wheat straw diet ($P < 0.05$). Wheat straw decreased the AID of Thr

and Val compared to the control diet ($P < 0.05$), but did not inhibit the SID of AA. The AID and SID of N and AA between the control and corn fiber diet were similar in the study. The inclusion of rice hulls reduced the AID of energy and N, the ATTD of energy, and the AHD of energy compared to the control group ($P < 0.05$). The AID, ATTD, and AHD of energy was lower in pigs fed wheat straw compared to the control ($P < 0.05$); however, wheat straw did not influence N digestibility. The AID, ATTD, and AHD of N and energy of corn fiber was similar to the control. For experiment 2 (Exp. 2), sugar beet pulp was fed at 4 different inclusion levels (0 g/kg, 100 g/kg, 200 g/kg, and 300 g/kg) in soybean meal, cornstarch-based diets to 20 35-kg barrows. Inclusion of sugar beet pulp linearly reduced the AID and SID of N and all indispensable and dispensable AA (linear, $P < 0.05$; quadratic, $P > 0.10$). The AID of energy and N decreased when sugar beet pulp was added to the diets (linear and quadratic, $P < 0.05$). The ATTD of energy was also reduced (linear and quadratic, $P < 0.05$), as well as the ATTD of N (linear, $P < 0.05$; quadratic, $P > 0.10$). There were no differences in AHD of energy and nitrogen among treatments. In conclusion, the SID and AID of N and AA and ATTD of energy and N is uniquely impacted by the source and inclusion level of fiber in diets fed to growing pigs.

Key words: Amino acids, corn fiber, fiber, growing pigs, rice hulls, sugar beet pulp, wheat straw

# Introduction

As the availability of nutrient dense grains and grain by-products decreases for animal producers, researchers are actively looking for alternative sources of sustainable energy and nutrients. Many alternative feedstuffs contain significant concentrations of fibrous components, which have been observed to hinder nutrient digestibility in nonruminant animals (Lenis et al., 1996). Dietary fiber can be defined as non-starch polysaccharides that are unable to be digested by endogenous enzymes and may be subject to microbial fermentation that occurs in the hindgut of nonruminants. Fiber that is digested by colonic bacteria can provide energy value to diets, particularly when fed to swine (Renteria Flores, 2003). Pigs are able to obtain energy from fibrous components indirectly from microbial fermentation that occurs in the hindgut. These microbes are able to degrade polysaccharides into smaller polysaccharides or monosaccharides, which are absorbed by the microbial cell (Muller, 2008). In response to this absorption, the microbes release volatile fatty acids (VFA) that can be used by other microbes or absorbed by the pig itself, which readily occurs in the large intestine (Barcroft et al., 1944). If absorbed by intestinal tissue, VFAs can be used by colon cells as an energy source, by the liver which uses propionate to synthesize glucose, and by muscle and adipose tissue (Wong et al., 2006).

Not only does the age and stage of production affect pigs' ability to digest fiber, the chemical components of fiber play a key role in digestion (Le Goff and Noblet, 2001; Renteria Flores, 2003). Sows have been found to readily digest the energy and nitrogen of diets containing significant soluble fiber fractions, and energy and nitrogen

digestibility was impaired upon the addition of insoluble fiber (Renteria Flores, 2003). Le Gall et al. (2009) attributed the reduction of total tract digestibility of energy in pigs to increasing the neutral detergent fiber (NDF) concentration of the diet. Lignin may also contribute to energy utilization reduction in swine diets (Wenk, 2001).

Along with impacting energy digestibility, dietary fiber can influence the nutrient absorption in swine diets. Soluble fiber can inhibit AID and SID of crude protein (CP) and AA in soybean meal-based diets fed to growing pigs (Mosenthin et al. 1994; Buraczewska et al., 2007). Purified wheat NDF has been shown to reduce the AID of many amino acids (Lenis et al., 1996), but feeding 10% cellulose and barley straw did not reduce the AID of most AA when added to soybean meal, cornstarch-based diets (Sauer et al., 1991).

As previous research found varying results of feeding different sources of fiber to pigs, studies were conducted to investigate the influence that different sources of insoluble and soluble fiber ingredients have on nutrient and energy digestibility. Corn fiber, rice hulls, and wheat straw were the insoluble ingredients investigated, as these products contain different levels of fibrous components. Corn fiber (hulls) consists of 15% cellulose, 35% hemicellulose, and 8% lignin in its fibrous fraction (Saha, 2003). Rice hulls contain 38% cellulose, 18% hemicellulose, and 22% lignin of it fiber components (Salanti et al., 2010), and wheat straw's fiber consists of 40% cellulose, 25% hemicellulose, and 15% lignin (del Rio et al., 2012). Sugar beet pulp was investigated due to its high content of soluble fiber, which has been observed to be fairly digestible when fed to pigs (Pieper et al., 2012; von Heimendahl et al., 2010).

Understanding that the optimum use of dietary fiber in swine nutrition has yet to be determined, researchers must continue to investigate the impact that different fiber types have on nutrient digestibility. Therefore, two experiments were designed to determine the impact that various insoluble and soluble fibrous ingredients have on energy and nutrient digestibility in pigs.

## Materials and Methods

All experimental protocols were approved by the Purdue Animal Care and Use Committee.

### Experimental Design

Hampshire × Duroc ×Yorkshire ×Landrace barrows (Exp. 1 BW: 45 ± 0.69 kg; Exp. 2 BW: 35 ± 0.10 kg) were obtained from the Purdue University Animal Research farm and used in a randomized crossover design with initial body weight as the blocking factor. Pigs were housed individually in floor pens with ad libitum access to water and 12 hours of artificial lighting in climate controlled rooms (22$^{o}$C). At the beginning of each period, pigs were weighed and allotted to block by body weight and treatment within each block. Experimental diets were fed to the pigs (19 pigs for Exp. 1; 20 pigs for Exp. 2) according to a 5 × 2 crossover arrangement with each period lasting 7 d, with randomization such that pigs did not receive the same diet in Period 2 as Period 1. Four days were allowed for the pigs to adapt to the experimental diets, followed by fecal collection on d 5 and a 2 d collection period of ileal digesta by attaching a plastic tubular bag to the externalized T-cannula on d 6 and 7. To reduce

proliferation of bacteria in the ileal samples, each bag contained 10 mL of 5% formic acid, and ileal contents were stored at -20°C between collections. Following the experiments, the ileal digesta was thawed and pooled for each pig for the 2 d collection, subsampled, and lyophilized. Daily feed allowance was given at 3% of BW of the smallest pig in each block at the beginning of the adaptation period, and feed was given in 2 equal portions at 0600 and 1800. Chromic oxide was incorporated into diets at 5 g/kg (as-fed basis) to calculate nutrient digestibility according to the index method.

Dietary Treatments

For each experiment, 4 diets were formulated to contain 16% CP with soybean meal (SBM) supplying most of the dietary AA and the fiber sources supplying fractional amounts of AA. Soybean meal and cornstarch were adjusted to allow for the inclusion of the fiber source. A nitrogen-free, semi-purified, cornstarch-based diet was fed to determine the endogenous flow of AA. Diets were formulated to meet current NRC requirements (2012). Over 2 periods, there were 8 replicates per experimental diet, and 7 (Exp. 1) or 8 (Exp. 2) replicates for the NFD. For Exp. 1, the experimental diets consisted of SBM control diet, SBM + corn hulls, SBM + rice hulls, and SBM + wheat straw diets (Table 3.1). The fiber ingredients were fed at 100g/kg of the diet (as-fed basis). For Exp. 2, the diets consisted of SBM and SBM + sugar beet pulp at 100 g/kg, 200 g/kg, and 300 g/kg (as-fed basis) (Table 3.2).

Cannulation Surgery

The cannulation procedure used in the current study was performed according to previous reports (Dilger et al., 2004). Pigs were fasted for 18 to 24h before being fitted with metallic ileal cannulas at the distal ileum, approximately 6 cm proximal to the

ileocecal junction. A Telazol mixture (containing 50 mg/mL each of tilet-amine HCl, zolazepam HCl, ketamine HCl [Fort Dodge Laboratories, Fort Dodge, IA], and xylazine HCl [Bayer Corp., Shawnee Mission, KS]) was administered intramuscularly at a dosage of 22.0 µL/kg of body weight to induce anesthesia of the pigs. After Telazol administration, the barrows were maintained under gas anesthesia with Halothane gas (Halocarbon Laboratories, River Edge, NJ) at 1.5 to 2.0% with an oxygen flow rate of 2.0L/min. Antibiotic therapy (Polyflex [ampicillin trihydrate]) given intramuscularly at 11.0 mg/kg body weight) was administered before and after the surgery in order prevent infection and alleviate the need for antibiotic treatment during the recovery period.

A longitudinal incision was made on the intestine, and the cannula was inserted into the ileum and secured with a continuous suture that extended to the barrel of the cannula. A circular defect was created in the body wall to allow the cannula to be exteriorized caudal to the last rib. Using a string attached to a bullet-shaped device threaded onto the cannula, the device and cannula was pulled through the defect and positioned appropriately. This method ensured that the structural integrity of the inserted cannula was not compromised. To secure the exteriorized cannula, a retainer plate and cap was secured onto the cannula barrel. Pigs were allowed at least 7 d to recover from the procedure before the start of the study. During recovery, the pigs were offered small amounts of a corn-soybean meal based diet, which satisfied or exceeded their nutrient requirements (NRC, 2012). Amount of feed offered was increased as the recovery improved with the pigs increasing in activity and appetite.

Chemical Analyses

Diets, ingredients, and freeze-dried ileal samples were ground to pass through a 0.5-mm screen before analysis. Diets and ingredients were analyzed for dry matter, energy, chromium, nitrogen, phosphorus, calcium, and amino acids. Ileal samples were analyzed for dry matter, chromium, nitrogen, and amino acids. Amino acid analyses were conducted at the Experimental Station Chemical Laboratory at the University of Missouri. For AA analysis, samples were hydrolyzed using 6 *N* HCl at 100$^{o}$C for 24h under nitrogen atmosphere. For the sulfur amino acids (methionine and cysteine), performic acid oxidation occurred prior to acid hydrolysis. Barium hydroxide was used to hydrolyze tryptophan during analysis. High-performance liquid chromatography after postcolumn derivatization was used to determine amino acid concentrations in hydrosylate (AOAC, 2000; 982.30 E [a, b, c]). Chromium concentration of the samples were determined by digesting the material in perchloric/nitric acids and measured by plasmic atomic emission spectroscopy method (AOAC, 2000: 990.08).The nitrogen content of the samples were determined by the Kjeltech method (Kjeltech 2300 Analyzer Unit, Hoganas, Sweden) following sulfuric acid digestion and by the combustion method (LECO FP Analyzer Model 602600, Leco Corp. Meriden, CT). Dietary calcium was determined by flame atomic absorption spectroscopy (Varian FS240, Varian Inc., Can Palo, CA), and phosphorus concentration was determined using ammonium molybdate according to Onyango et al. (2004). Diets, ingredients, and ileal and fecal samples were analyzed for gross energy content and determined by adiabatic bomb calorimeter (Parr 1261 bomb calorimeter; Parr Instruments Co., Moline IL).

Calculations

In accordance with calculations described by Dilger et al. (2004) basal endogenous loss (BEL) of AA can be determined with the index method using the following equation:

$$BEL = N_O \times (Cr_I/Cr_O)$$

where $N_O$ is the nutrient concentration of the nitrogen-free group of pigs, $Cr_I$ refers to the chromium concentration of the nitrogen-free diet, and $Cr_O$ represents the chromium concentration of the ileal output from pigs fed the nitrogen-free diet. The endogenous losses of N and AA of these pigs were averaged to correct apparent ileal digestibility. Apparent ileal digestibility (AID) was calculated with the following equation:

$$AID = [1- (Cr_I/Cr_o) \times (N_O/N_I)] \times 100$$

where $Cr_I$ is the chromium concentration of the diet consumed, $Cr_O$ represents the chromium concentration of the ileal output, $N_O$ is the nutrient output (N, AA, or energy) in the ileal digesta, and $N_I$ refers to the nutrient concentration of the diet consumed. Standardized ileal digestibility (SID) can be calculated from the following equation:

$$SID = AID + [(BEL/N_i) \times 100]$$

where AID is the apparent ileal nutrient digestibility, BEL is the basal endogenous loss of nutrient, and $N_i$ is the nutrient concentration of the diet. Apparent total tract digestibility (ATTD) can be calculated from the following equation:

$$ATTD = [1- (Cr_I/Cr_o) \times (N_O/N_I)] \times 100$$

where $Cr_I$ is the chromium concentration of the diet consumed, $Cr_O$ represents the chromium concentration of the fecal output, $N_O$ is the nutrient output (N or energy) in

the feces, and $N_I$ refers to the nutrient concentration of the diet consumed. Apparent hindgut digestibility (AHD) can be calculated from the following equation:

$$AHD = [1- (Cr_I/Cr_o) \times (N_O/N_I)] \times 100$$

where $Cr_I$ is the chromium concentration of the ileal digesta entering the hindgut, $Cr_O$ represents the chromium concentration of the fecal ouput, $N_O$ is the nutrient output (N or energy) in the feces, and $N_I$ refers to the nutrient concentration of the ileal digesta entering the hindgut.

Statistical Analysis

Data was analyzed using the MIXED procedure of SAS (2012) appropriate for randomized crossover design, with pig serving as the experimental unit. The model included the fixed effects of the diet, and period and pig were random effects. To calculate AHD of treatments, a split-plot design was used, with the model including fixed effects of the whole plot (diet) and subplot (site) and random effects of period and pig. Means were calculated using the LSMEANS statement. For Experiment 1, means were separated using the PDIFF option when significant *F*-tests for treatment were observed. For Experiment 2, means were separated by linear and quadratic contrasts. An α value of 0.05 was used to determine significant differences among means.

## Results

### Composition of Diets and Ingredients

Diets in the experiments were formulated to provide 160 g/kg of CP and a Ca:P ratio of 1.2 (Tables 3.1 and 3.2). Diet analysis revealed slight differences among

treatments due to variability of nutrient composition in the experimental ingredients compared to values provided by the NRC (2012). The CP content of the diets in Exp. 1 were fairly consistent except for the diet containing rice hulls, which was revealed to have a CP of 126 g/kg, which may be due to rice hulls only providing 32 g/kg to the diet (Tables 3.3 and 3.1). The Ca:P ratio was fairly consistent among treatments in Exp. 1 (Table 3.1). In Exp. 2, all diets were similar in CP and Ca:P content, as the analysis of SBM and sugar beet pulp revealed nutrient compositions similar to that provided by the NRC (2012) (Tables 3.4 to 3.6). The CP for the SBM control diet appeared slightly higher, but the reason for this is unknown as the CP content of SBM was analyzed to contain 447 g/kg, which matches the predicted NRC value (2012).

Endogenous Loss of AA

As previously mentioned, the SID of AA requires the measurement of endogenous loss of AA, which can be obtained by feeding a nitrogen-free diet to the animals. Calculation of SID should provide more accurate determination of AA digestibility than AID. Tables 3.7 and 3.8 reveal a similar trend in endogenous losses of N and AA with pigs from Exp. 1 having greater losses of AA. This is most likely due to the pigs in Exp.1 being more mature and heavier than those in Exp. 2. In both experiments, the endogenous losses of Pro and Gly were much higher and more variable than other AA, which can result in unrepresentable values of SID for these AA in diets fed to pigs.

AID and SID of N and AA in Exp.1

Inclusion of rice hulls to the SBM-based diets reduced the AID and SID of N, Arg, Ile, Trp, and Cys compared to the control and corn fiber diets (Tables 3.9 and 3.10)

($P < 0.05$). Rice hulls also had lower AID of N and Glu and lower SID of N and Leu compared to the wheat straw diet ($P < 0.05$). The AID of Thr and Val was reduced in the diet containing wheat straw compared to the control ($P < 0.05$), but wheat straw did not affect the SID of N and AA. Corn fiber did not influence the AID or SID of N and AA compared to the control.

AID and SID of N and AA for Exp. 2

Sugar beet pulp inclusion reduced the AID and SID of all indispensable and dispensable amino acids (linear, $P < 0.05$). However, there is no quadratic response when sugar beet pulp was added to the diets (quadratic, $P > 0.10$).

AID, ATTD, and AHD of Energy and N for Exp. 1

Corn fiber did not impact the AID, ATTD, and AHD of N and energy compared to the control diet when fed to pigs (Table 3.13). Rice hulls reduced the AID of energy and N, the ATTD of energy, and the AHD of energy compared to the control diet ($P < 0.05$). Wheat straw did not appear to influence N digestibility, but did reduce the AID, ATTD, and AHD of energy compared to the control ($P < 0.05$).

AID, ATTD, and AHD of Energy and N for Exp. 2

As seen in Table 3.14, addition of sugar beet pulp reduced the AID of energy and nitrogen when fed to pigs (linear and quadratic, $P < 0.05$). The ATTD of energy was also observed to decrease with sugar beet pulp inclusion of the diets (linear and quadratic, $P < 0.05$), along with a linear, but not quadratic, decrease of ATTD of nitrogen (linear, $P < 0.05$). Even though more fiber was available for colonic fermentation as sugar beet pulp inclusion increased, the AHD of fiber did not differ among ingredient (linear and quadratic, $P > 0.10$).

## Discussion

As biofuel by-products become more available to swine producers, research investigating the nutritional value and potential application of alternative ingredients should be conducted. With many of these alternative feeds containing a high level of fiber, observations of fiber's influence on nutrient and energy digestibility must be documented. The influence of corn fiber, rice hulls, wheat straw, and sugar beet pulp on the digestibility of energy, N, and AA in diets fed to swine was investigated in the present study. The unique nutrient and chemical composition of these ingredients revealed by the experiments and the review of related literature in this study should provide insight into the appropriate inclusion of fiber in diets fed to pigs.

Corn fiber is a common by-product of the ethanol industry and appears to be a potential energy source in swine diets. Analysis of corn fiber revealed it to contain 11% CP, which agrees with previous reports (de Godoy et al., 2009). Containing a low concentration of lignin and high concentrations of hemicellulose and cellulose, corn fiber does not inhibit the digestibility of energy, N, and AA in pigs fed SBM-based diets. Similar findings exist in previous reports, as fibers containing high levels of cellulose and hemicellulose, such as barley straw, did not reduce nutrient digestibility in pigs (Sauer et al., 1991). Even though hemicellulose has a high water-binding capacity, which may affect digesta viscosity during digestion (Shelton and Lee, 2000), it appears that effect is not observed when corn fiber is fed at 100 g/kg to pigs.

Rice hulls, a by-product of rice bran manufacturing, appears to severely inhibit the digestion of energy, N, and AA in diets fed to pigs. This decrease in nutrient digestibility may be attributed to the high content of lignin, which has been found to be

22% of the insoluble fiber fraction in rice hulls (Salanti et al., 2010). Lignin is one of the strongest binding agents in fiber and has been observed to reduce hindgut fermentation of cellulose and decrease nutrient absorption in pigs (Shi and Noblet, 1993; Kritchevsky, 1988). Lignin also provides little to no energy value to a feed ingredient, as this molecule remains undigested by colonic microbes (Graham et al., 1986), which agrees with the lower ATTD and AHD of energy from rice hulls observed in this study.

Wheat straw was observed to impede the AID, but not SID, of some AA and did not impact the ATTD or AHD of N compared to the control diet, revealing little interference of nutrient digestibility of wheat straw. These observations agree with previous reports that observed no influence of barley straw on protein digestibility in pigs (Sauer et al., 1991). As wheat straw contains mostly cellulose and little lignin (40% cellulose, 15% lignin) in its fibrous components, researchers have found that cellulose does not affect nutrient digestibility (Li et al., 1994). The hindgut and total digestibility of energy was lower in wheat straw compared to the control diet, which may be due to its lignin content hindering microbial attack of cellulose in the feed ingredient as reported by other studies (Shi and Noblet, 1993; Kritchevsky, 1988).

As the solubility of fibers have been observed to impact energy and nutrient digestibility, varying levels of sugar beet pulp inclusion was evaluated in the study (Renteria Flores, 2003). A major by-product of sugar beet production, sugar beet pulp appears to decrease the digestibility of AA, N, and energy in diets fed to pigs. A reduction of total tract digestibility of N and energy was only observed when sugar beet pulp added to the diets of growing pigs. Even though there appears to be some hindgut

fermentation of the ingredient, the AHD of sugar beet pulp diets was not different than the control diet. Soluble fiber has been found to provide readily digestible energy to swine (von Heimendahl et al., 2010), and feeding sugar beet pulp up to 10% of the diet results in high ATTD of energy. However, soluble fiber also maintains high water-binding capacity due to beta (1-3) linkages in the molecular structure which can increase the viscosity of digesta and reduce nutrient digestibility, which was observed in the current study (Oakenfull, 2001; Graham et al., 1986). The current study determined that the inclusion of sugar beet pulp results in a decrease in the digestibility of energy and nitrogen (linear and quadratic response) when ileal and total tract digestibility was calculated. However, pigs were not able to utilize more energy from the added fiber via hindgut fermentation, implying that soluble fiber may contain components that resist microbial digestion of the dietary fiber.

Researchers have found that increasing the NDF fraction of diets result in a decrease in nutrient digestibility by pigs (Lenis et al., 1996; Dilger et al., 2004). As NDF refers to a sum of cellulose, hemicellulose, and lignin components, this value appears be too vague to properly predict nutrient digestibility, as the current study revealed less inhibition of wheat straw than rice hulls even though wheat straw (80% NDF) and rice hulls (78% NDF) have similar NDF values (Salanti et al., 2010; del Rio et al., 2012). The current study and previous reports reveal that hemicellulose and cellulose do not always hinder nutrient digestibility and may be fermented in the hindgut of pigs, and lignin content of fiber may be the major reason for dietary fiber reducing nutrient digestibility (Li et al., 1994; Kritchevsky, 1988).

In conclusion, addition of corn fiber did not decrease the energy, N, or AA digestibility of soybean meal. Wheat straw inclusion revealed no reduction of total tract nutrient digestibility but less energy digestibility than the control diet. Rice hulls significantly reduced the AA, N, and energy digestibility of diets, which may be due to its high lignin content, as observed by regression analysis. Sugar beet pulp fed at low levels revealed a decrease in nutrient digestibility but similar total tract digestibility of energy compared to the control diet. When fed at higher levels, sugar beet pulp resulted in lower digestibility of N, AA, and energy compared to diets containing no additional fiber. These studies reveal the unique impacts of different fiber sources on nutrient and energy digestibility in growing pigs, and more research is required to better understand the utilization of high fibrous alternative ingredients in animal production.

# References

AOAC. 2000. Official Methods of Analysis. 17th ed. Assoc. Offic. Anal. Chem., Arlington, VA.

Barcroft, J., R. A. McAnally, and A. T. Phillipson. 1944. Absorption of VFA from the alimentary tract of the sheep and other animals. J. Exp. Biol. 20:120-132.

Buraczewska, L., E. Swiech, A. Tusnio, M Taciak, M. Ceregrzyn, and W. Korczynski. 2007. The effect of pectin in amino acid digestibility and digesta viscosity, motility and morphology of the small intestine, and on N-balance and performance of young pigs. Livest. Sci. 109:53-56.

de Godoy, M., L. Bauer, C. Parsons, G. Fahey, Jr. 2009. Select corn coproducts from the ethanol industry and their potential as ingredients in pet foods. J Anim Sci. 87:189–199.

del Rio, J., J. Rencoret, P. Prinsen, A. Martinez, J. Ralph, and A. Gutierrez. 2012. Structural Characterization of Wheat Straw Lignin as Revealed by Analytical Pyrolysis, 2D-NMR, and Reductive Cleavage Methods. J. Agr. Food Chem. 60:5922-5935.

Dilger, R. N., J. S. Sands, D. Ragland, and O. Adeola. 2004. Digestibility of nitrogen and amino acids in soybean meal with added soyhulls. J. Anim. Sci. 82:715-724.

Graham, H., K. Hesselman, and P. Aman. 1986. The influence of wheat bran and sugar-beet pulp on the digestibility of dietary components in a cereal-based pig diet. J. Nutr. 116:242-251.

Kritchevsky, D. 1988. Dietary Fiber. Ann. Rev. Nutr. 8:301-328.

Le Gall, M., M. Warpechowski, Y. Jaguelin-Peyraud, and J. Noblet. 2009. Influence of dieteary fibre level and pelleting on the digestibility of energy and nutrients in growing pigs and adult sows. Animal 3:352-359.

Le Goff, G., and J. Noblet. 2001. Comparative digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 80:2418-2427.

Lenis, N. T. , J. E. Lindberg, and B. Ogle. 2006. Digestibility and nitrogen retention of diets containing different levels of fibre in local (Mong Cai), F1 (Mong Cai x Yorkshire) and exotic (Landrace x Yorkshire) growing pigs in Vietnam. J. Anim. Physiol. Anim. Nutr. 91:297-303.

Li, S., W. C. Sauer, and R.T. Hardin. 1994. Effect of dietary fibre level on amino acid digestibility in young pigs. Can. J. Anim. Sci. 74:327-333.

Mosenthin, R., W. C. Sauer, and F. Ahrens. 1994. Dietary pectin's effect on ileal and fecal amino acid digestibility and exocrine pancreatic secretions in growing pigs. J. Nutr. 124:1222-1229.

Muller, V. 2008. Bacterial Fermentation. *Pages 1-8 Encyclopedia of Life Sciences*. John Wiley & Sons. Ltd. Chichester. Doi: 10.1002/9780470015902.a0001415.pub2.

National Research Council, 2012. Nutrient Requirements of Swine. National Academy of Press, Washington D.C.

Oakenfull, D. 2001. Physical chemistry of dietary fiber. Pages 33-47 in *Dietary Fiber in Human Nutrition.* 3rd ed. G. A. Spiller, ed. CRC Press, Boca Raton, FL.

Pieper, R., S. Kroger, J. Richter, J. Wang, L. Martin, J. Bindelle, J. Htoo, D. von Smolinski, W. Vahjen, J. Zentek, and A. Van Kessel. 2012. Fermentable fiber ameliorates fermentable protein-induced changes in microbial ecology, but not the mucosal response, in the colon of piglets. J. Nutr. 141:661-667.

Renteria Flores, J. A. 2003. Effects of soluble and insoluble dietary fiber on diet digestibility and sow performance. PhD. Dissertation, Univ. of Minnesota, St. Paul.

Saha, B.C. 2003. Hemicellulose bioconversion. J. Ind. Microbiol. Biotechnol. 30: 279-291.

Salanti, , A., L. Zoia, M. Orlandi, F. Zanini, G. Elegir. 2010. Structural Characterization and Antioxidant Activity Evaluation of Lignins from Rice Husk. J. Agric. Food Chem. 58:10049–10055.

Sauer, W. C., R. Mosenthin, F. Ahrens, and L. A. den Hartog. 1991. The effect of source of fiber on ileal and fecal amino acid digestibility and bacterial nitrogen excretion in growing pigs. J. Anim. Sci. 69:4070-4077.

Shelton, D. R. and W. J. Lee. 2000. Cereal carbohydrates. Page 385-316 in *Handbook of Cereal Science and Technology*. 2nd ed. K . Kulp and J. G. Ponte, eds. Marcel Dekker, New York, NY.

Shi, X. S. and J. Noblet. 1993. Contribution of the hindgut to digestion of diets in growing pigs and adult sows: Effect of diet composition. Livest. Prod. Sci. 34:237-252.

von Heimendahl E., G. Breves, and H. J. Abel. 2010. Fiber related digestive processes in three different breeds of pigs. J. Anim. Sci. 88:972–981.

Wenk, C. 2001. The role of dietary fibre in the digestive physiology of the pig. Anim. Feed Sci. Technol. 90:21-33.

Wong, J. M., R. de Souza, C. W. Kendall, A. Emam, and D. J. Jenkins. 2006. Colonic health: Fermentation and short chain fatty acids. J. Clin. Gastroenterol. 40:235-243.

**Table 3.1 Ingredient composition of experimental diets, as-fed basis, for Exp. 1**

| Diet | SBM | Corn Fiber | Rice Hulls | Wheat Straw | Nitrogen-free |
|---|---|---|---|---|---|
| *Ingredients, g/kg* | | | | | |
| Corn Fiber | 0 | 100 | 0 | 0 | 0 |
| Rice Hulls | 0 | 0 | 100 | 0 | 0 |
| Wheat Straw | 0 | 0 | 0 | 100 | 0 |
| Soybean Meal, 45%CP | 360 | 357 | 353 | 352 | 0 |
| Corn Starch | 484 | 387 | 391 | 392 | 751 |
| Dextrose | 100 | 100 | 100 | 100 | 100 |
| Soy oil | 0 | 0 | 0 | 0 | 30 |
| Solka-floc | 0 | 0 | 0 | 0 | 50 |
| Chromic Oxide Prmx [1] | 25 | 25 | 25 | 25 | 25 |
| Monocalcium Phosphate [2] | 18 | 18 | 18 | 18 | 30 |
| Limestone [3] | 6 | 6 | 6 | 6 | 3 |
| Salt | 4 | 4 | 4 | 4 | 4 |
| Vitamin Premix [4] | 2 | 2 | 2 | 2 | 2 |
| Mineral Premix [5] | 1 | 1 | 1 | 1 | 1 |
| Selenium Premix [6] | 1 | 1 | 1 | 1 | 1 |
| Potassium carbonate | 0 | 0 | 0 | 0 | 4 |
| Magnessium oxide | 0 | 0 | 0 | 0 | 1 |
| Total | 1000 | 1000 | 1000 | 1000 | 1000 |

[1] 5 g Chromic oxide plus 20 g cornstarch
[2] 16% Ca, 21% P
[3] 38% Ca
[4] Vitamin premix contained per gram of premix: vitamin A, 2640 IU; vitamin $D_3$, 264 IU; vitamin E, 17.6 IU; vitamin K activity, 2.4 mg; menadione, 880 µg; vitamin $B_{12}$, 15.4 µg; riboflavin, 3.52 mg; D-pantothenic acid, 8.8 mg; niacin,13.2 mg.
[5]Mineral premix contained per gram of premix: Cu (as copper chloride), 9 mg; I (Ethylenediamine Dihydroiodide (EDDI)), 0.36 mg; Fe (as ferrous carbonate), 194 mg; Mn (as manganese oxide), 17 mg; and Zn (as zinc oxide), 149 mg
[6] Supplied 300 µg of Se per kilogram of diet

**Table 3.2 Ingredient composition of experimental diets, as-fed basis, for Exp. 2**

| Diets | 0% SBP[1] | 10% SBP | 20% SBP | 30% SBP | NFD |
|---|---|---|---|---|---|
| *Ingredients, g/kg* | | | | | |
| Sugar Beet Pulp | 0 | 100 | 200 | 300 | 0 |
| SBM, 45% CP | 353 | 333 | 312 | 292 | 0 |
| Corn Starch | 491 | 413 | 336 | 257 | 748 |
| Dextrose | 100 | 100 | 100 | 100 | 100 |
| Soy oil | 0 | 0 | 0 | 0 | 30 |
| Solka-floc | 0 | 0 | 0 | 0 | 50 |
| Chromic Oxide Prmx[2] | 25 | 25 | 25 | 25 | 25 |
| Monocalcium Phosphate [3] | 15 | 15 | 16 | 16 | 29 |
| Limestone [4] | 9 | 7 | 5 | 3 | 7 |
| Salt | 4 | 4 | 4 | 4 | 4 |
| Vitamin Premix [5] | 2 | 2 | 2 | 2 | 2 |
| Mineral Premix [6] | 1 | 1 | 1 | 1 | 1 |
| Selenium Premix [7] | 1 | 1 | 1 | 1 | 1 |
| Potassium carbonate | 0 | 0 | 0 | 0 | 4 |
| Magnessium oxide | 0 | 0 | 0 | 0 | 1 |
| Total | 1000 | 1000 | 1000 | 1000 | 1000 |

[1]Sugar Beet Pulp

[2] 5 g Chromic oxide plus 20 g cornstarch
[3] 16% Ca, 21% P
[4] 38% Ca
[5] Vitamin premix contained per gram of premix: vitamin A, 2640 IU; vitamin $D_3$, 264 IU; vitamin E, 17.6 IU; vitamin K activity, 2.4 mg; menadione, 880 µg; vitamin $B_{12}$, 15.4 µg; riboflavin, 3.52 mg; D-pantothenic acid, 8.8 mg; niacin,13.2 mg.
[6]Mineral premix contained per gram of premix: Cu (as copper chloride), 9 mg; I (Ethylenediamine Dihydroiodide (EDDI)), 0.36 mg; Fe (as ferrous carbonate), 194 mg; Mn (as manganese oxide), 17 mg; and Zn (as zinc oxide), 149 mg
[7] Supplied 300 µg of Se per kilogram of diet

**Table 3.3 Analyzed composition of ingredients for Exp. 1, as-fed basis**

| Item | SBM | Corn Fiber | Rice Hulls | Wheat Straw |
|---|---|---|---|---|
| DM, g/kg | 911 | 940 | 941 | 971 |
| Protein, g/kg | 446 | 116 | 32 | 51 |
| GE, kcal / kg | 4192 | 4371 | 3447 | 4114 |
| Ca, g/kg | 4.0 | 0.3 | 0.9 | 0.6 |
| P, g/kg | 5.4 | 2.7 | 0.4 | 0.4 |
| | | | | |
| Indispensable AA, g/kg | | | | |
| Arg | 32.4 | 4.0 | 1.0 | 0.8 |
| His | 10.9 | 3.5 | 0.4 | 0.4 |
| Ile | 20.9 | 3.7 | 0.9 | 0.9 |
| Leu | 34.7 | 12.3 | 1.6 | 1.8 |
| Lys | 28.7 | 3.3 | 1.3 | 1.2 |
| Met | 6.0 | 1.7 | 0.3 | 0.3 |
| Phe | 23.3 | 5.2 | 1.1 | 1.0 |
| Thr | 17.3 | 3.9 | 1.0 | 0.9 |
| Trp | 5.3 | 0.6 | 0.4 | 0.4 |
| Val | 21.7 | 5.2 | 1.3 | 1.2 |
| Dispensable AA, g/kg | | | | |
| Ala | 19.30 | 7.00 | 1.40 | 1.30 |
| Asp | 50.10 | 5.80 | 2.10 | 1.80 |
| Cys | 5.90 | 2.30 | 0.30 | 0.40 |
| Glu | 79.60 | 18.10 | 2.90 | 3.00 |
| Gly | 19.30 | 4.30 | 1.20 | 1.10 |
| Pro | 23.10 | 10.10 | 1.70 | 1.60 |
| Ser | 20.00 | 4.20 | 0.90 | 0.90 |
| Tyr | 16.20 | 3.30 | 0.40 | 0.40 |
| Total | 437.00 | 100.30 | 205.00 | 198.00 |

**Table 3.4 Analyzed composition of ingredients for Exp. 2, as-fed basis**

| Item | SBM | Sugar Beet Pulp |
|---|---|---|
| DM, g/kg | 940 | 929 |
| Protein, g/kg | 447 | 89.9 |
| GE, kcal / kg | 4323 | 3829 |
| Ca, g/kg | 8.0 | 2.8 |
| P, g/kg | 0.9 | 6.7 |
| Indispensable AA, g/kg | | |
| Arg | 32.5 | 2.8 |
| His | 12.2 | 2.8 |
| Ile | 20.5 | 3.4 |
| Leu | 34.5 | 5.8 |
| Lys | 28.9 | 4.2 |
| Met | 6.1 | 1.3 |
| Phe | 22.9 | 3.6 |
| Thr | 17.4 | 4.1 |
| Trp | 5.6 | 0.7 |
| Val | 21.5 | 5.4 |
| Dispensable AA, g/kg | | |
| Ala | 19.2 | 4.1 |
| Asp | 50.2 | 6.7 |
| Cys | 6.3 | 1.1 |
| Glu | 80 | 8.5 |
| Gly | 19.3 | 3.8 |
| Pro | 22.9 | 4.3 |
| Ser | 20.2 | 3.8 |
| Tyr | 16.3 | 3.2 |
| Total | 440.5 | 75.3 |

**Table 3.5 Analyzed composition of experimental diets for Exp. 1, as-fed basis**

| Diet | SBM | Corn Fiber | Rice Hulls | Wheat Straw | Nitrogen-free |
|---|---|---|---|---|---|
| GE, kcal / kg | 3683 | 3724 | 3506 | 3681 | 3684 |
| Protein, g/kg | 141 | 150 | 126 | 151 | 4 |
| Ca, g/kg | 7.6 | 7.4 | 8.1 | 8.1 | 6.5 |
| P, g/kg | 5.2 | 5.6 | 5.3 | 5.5 | 5.2 |
| Ca:P | 1.5 | 1.3 | 1.5 | 1.5 | 1.3 |
| Indispensable AA, g/kg | | | | | |
| Arg | 10.7 | 9.9 | 10.3 | 10.2 | 0.1 |
| His | 3.7 | 3.6 | 3.6 | 3.6 | 0.0 |
| Ile | 7.3 | 6.8 | 7.0 | 7.0 | 0.2 |
| Leu | 12.2 | 11.9 | 11.7 | 11.7 | 0.4 |
| Lys | 9.9 | 9.1 | 9.7 | 9.6 | 0.1 |
| Met | 2.1 | 2.0 | 2.0 | 1.9 | 0.0 |
| Phe | 8.1 | 7.6 | 7.7 | 7.7 | 0.2 |
| Thr | 5.9 | 5.6 | 5.8 | 5.7 | 0.1 |
| Trp | 2.1 | 1.8 | 1.8 | 1.8 | <0.4 |
| Val | 7.6 | 7.2 | 7.3 | 7.2 | 0.2 |
| Dispensable AA, g/kg | | | | | |
| Ala | 6.70 | 6.50 | 6.70 | 6.50 | 0.20 |
| Asp | 17.20 | 15.80 | 16.80 | 16.50 | 0.20 |
| Cys | 2.10 | 2.10 | 2.00 | 1.90 | 0.00 |
| Glu | 27.80 | 26.20 | 27.00 | 26.70 | 0.50 |
| Gly | 6.50 | 6.30 | 6.60 | 6.30 | 0.10 |
| Pro | 7.80 | 7.80 | 7.90 | 7.90 | 0.60 |
| Ser | 6.80 | 6.40 | 6.80 | 6.70 | 0.10 |
| Tyr | 4.90 | 4.70 | 4.60 | 4.70 | 0.10 |
| Total | 150.50 | 142.50 | 146.60 | 144.80 | 3.60 |

**Table 3.6 Analyzed composition of experimental diets for Exp. 2, as-fed basis**

| Diet | 0% SBP | 10% SBP | 20% SBP | 30% SBP | Nitrogen-free |
|---|---|---|---|---|---|
| GE, kcal / kg | 3834 | 3831 | 3891 | 3814 | 3731 |
| Protein, g/kg | 177 | 164 | 158 | 154 | 2 |
| Ca, g/kg | 6.7 | 6.9 | 6.7 | 6.8 | 7.1 |
| P, g/kg | 5.3 | 5.4 | 5.6 | 5.5 | 6 |
| Ca:P | 1.3 | 1.3 | 1.2 | 1.2 | 1.2 |
| Indispensable AA, g/kg | | | | | |
| Arg | 12.2 | 10.3 | 9.3 | 9.7 | 0.1 |
| His | 4.7 | 4.2 | 4.0 | 4.4 | 0.1 |
| Ile | 7.9 | 6.7 | 6.4 | 6.7 | 0.1 |
| Leu | 13.6 | 11.6 | 10.9 | 11.6 | 0.4 |
| Lys | 11.3 | 9.7 | 9.3 | 9.9 | 0.2 |
| Met | 2.3 | 2.0 | 1.9 | 2.1 | 0.0 |
| Phe | 8.9 | 7.7 | 7.3 | 7.5 | 0.2 |
| Thr | 6.8 | 6.0 | 5.8 | 6.2 | 0.1 |
| Trp | 2.3 | 2.3 | 2.0 | 1.9 | 0.4 |
| Val | 8.3 | 7.3 | 7.0 | 7.6 | 0.2 |
| Dispensable AA, g/kg | | | | | |
| Ala | 7.70 | 6.70 | 6.40 | 6.90 | 0.30 |
| Asp | 19.80 | 16.80 | 15.70 | 16.50 | 0.30 |
| Cys | 2.30 | 2.00 | 1.90 | 2.10 | 0.00 |
| Glu | 31.70 | 26.60 | 24.60 | 25.60 | 0.60 |
| Gly | 7.60 | 6.60 | 6.40 | 6.80 | 0.20 |
| Pro | 9.00 | 7.80 | 7.60 | 8.30 | 0.40 |
| Ser | 8.10 | 7.00 | 6.70 | 7.20 | 0.20 |
| Tyr | 5.90 | 5.10 | 4.90 | 5.20 | 0.20 |
| Total | 172.00 | 149.00 | 140.20 | 149.40 | 4.10 |

**Table 3.7 Endogenous nutrient losses (mg/kg of DMI) of nitrogen and amino acids at the terminal ileum[a] for Exp. 1**

| | | Range[b] | | |
|---|---|---|---|---|
| Item | Average | min | max | SD |
| Nitrogen | 3605 | 1656 | 6450 | 1934 |
| Indispensable AA | | | | |
| Arg | 750 | 326 | 1169 | 275 |
| His | 260 | 142 | 481 | 119 |
| Ile | 428 | 235 | 613 | 144 |
| Leu | 677 | 339 | 919 | 248 |
| Lys | 481 | 26 | 898 | 368 |
| Met | 95 | 26 | 173 | 48 |
| Phe | 410 | 209 | 561 | 151 |
| Thr | 714 | 378 | 1007 | 236 |
| Trp | 182 | 117 | 259 | 56 |
| Val | 756 | 391 | 1044 | 257 |
| Dispensable AA | | | | |
| Ala | 774 | 365 | 1044 | 286 |
| Asp | 1053 | 495 | 1482 | 391 |
| Cys | 197 | 104 | 284 | 71 |
| Glu | 1183 | 574 | 1712 | 441 |
| Gly | 2274 | 939 | 3436 | 1018 |
| Pro | 7531 | 2959 | 14445 | 3916 |
| Ser | 700 | 378 | 1002 | 224 |
| Tyr | 333 | 183 | 481 | 122 |
| Total | 19057 | 8473 | 30394 | 7503 |

**[a]n = 7 pigs**
**[b]Minimum to maximum**

**Table 3.8 Endogenous nutrient losses (mg/kg of DMI) of nitrogen and amino acids at the terminal ileum[a] for Exp. 2**

| | | Range[b] | | |
|---|---|---|---|---|
| Item | Average | min | max | SD |
| Nitrogen | 2213 | 1117 | 3352 | 777 |
| Indispensable AA | | | | |
| Arg | 427 | 144 | 734 | 218 |
| His | 165 | 110 | 201 | 36 |
| Ile | 247 | 159 | 309 | 55 |
| Leu | 452 | 294 | 572 | 103 |
| Lys | 443 | 257 | 636 | 120 |
| Met | 62 | 37 | 82 | 16 |
| Phe | 275 | 171 | 340 | 61 |
| Thr | 461 | 306 | 557 | 99 |
| Trp | 88 | 61 | 114 | 17 |
| Val | 440 | 269 | 541 | 103 |
| Dispensable AA | | | | |
| Ala | 516 | 294 | 734 | 140 |
| Asp | 646 | 379 | 832 | 156 |
| Cys | 137 | 86 | 179 | 32 |
| Glu | 749 | 477 | 974 | 172 |
| Gly | 1195 | 511 | 1925 | 540 |
| Pro | 4050 | 786 | 8434 | 2971 |
| Ser | 431 | 257 | 555 | 113 |
| Tyr | 235 | 147 | 294 | 53 |
| Total | 11167 | 5115 | 18042 | 4677 |

**[a]n = 8 pigs**
**[b]Minimum to maximum**

**Table 3.9 Apparent ileal digestibility of N and AA in experimental diets for Exp. 1[1]**

| Items | Soybean Meal | Corn Fiber | Rice Hulls | Wheat Straw | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen | 69.1[a] | 77.0[a] | 53.2[b] | 70.9[a] | 2.93 | <0.0001 |
| Indispensable AA, % | | | | | | |
| Arg | 89.4[a] | 90.3[a] | 84.7[b] | 88.4[ab] | 1.40 | <0.0001 |
| His | 84.7 | 85.3 | 73.6 | 82.5 | 3.89 | <0.0001 |
| Ile | 81.4[a] | 81.8[a] | 76.1[b] | 78.5[ab] | 1.42 | <0.0001 |
| Leu | 81.9[ab] | 83.1[a] | 76.8[b] | 78.8[ab] | 1.61 | <0.0001 |
| Lys | 84.5 | 84.8 | 84.2 | 82.1 | 2.53 | 0.8075 |
| Met | 87.1 | 87.1 | 83.3 | 84.7 | 1.33 | 0.0689 |
| Phe | 82.9[ab] | 83.8[a] | 78.2[b] | 80.7[ab] | 1.33 | <0.0001 |
| Thr | 70.3[a] | 73.4[a] | 64.5[b] | 67.1[ab] | 2.31 | <0.0001 |
| Trp | 80.6[a] | 81.7[a] | 71.2[b] | 74.1[ab] | 1.75 | <0.0001 |
| Val | 75.2[a] | 76.5[a] | 68.1[b] | 70.0[b] | 1.96 | <0.0001 |
| Dispensable AA, % | | | | | | |
| Ala | 74.1[ab] | 77.5[a] | 69.0[b] | 70.8[ab] | 2.24 | <0.0001 |
| Asp | 76.5[ab] | 78.0[a] | 70.7[b] | 74.5[ab] | 1.67 | <0.0001 |
| Cys | 70.2[ab] | 73.6[a] | 60.3[c] | 64.5[bc] | 2.81 | <0.0001 |
| Glu | 83.5[ab] | 86.0[a] | 77.5[b] | 83.0[ab] | 1.80 | 0.0016 |
| Gly | 61.8[ab] | 69.4[a] | 52.9[b] | 62.2[ab] | 3.81 | <0.0001 |
| Pro | 59.4 | 69.3 | 46.0 | 70.7 | 8.30 | 0.0546 |
| Ser | 75.8 | 77.9 | 71.3 | 73.9 | 1.79 | 0.1511 |
| Tyr | 79.7[ab] | 81.3[a] | 75.1[b] | 77.6[ab] | 1.54 | <0.0001 |
| Mean | 78.9[ab] | 81.1[a] | 72.8[b] | 77.6[ab] | 1.91 | <0.0001 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ, $P < 0.05$**

**Table 3.10 Standardized ileal digestibility of N and AA in experimental diets for Exp. 1[1]**

| Items | Soybean Meal | Corn Fiber | Rice Hulls | Wheat Straw | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Nitrogen | 81.6[a] | 92.6[a] | 61.5[b] | 85.8[a] | 4.6 | 0.0003 |
| Indispensable AA, % | | | | | | |
| Arg | 94.3[a] | 95.6[a] | 89.9[b] | 92.8[ab] | 1.03 | 0.0101 |
| His | 88 | 93.4 | 80.7 | 85.5 | 3.44 | 0.1644 |
| Ile | 86.2[a] | 87.1[a] | 81.3[b] | 83.1[ab] | 1.23 | 0.0151 |
| Leu | 86.0[ab] | 87.8[a] | 81.3[b] | 82.3[a] | 1.23 | 0.0173 |
| Lys | 88.1 | 87.6 | 86.9 | 85.3 | 1.98 | 0.8075 |
| Met | 90.5 | 91.2 | 87.1 | 87.6 | 0.92 | 0.0689 |
| Phe | 87.1[ab] | 88.4[a] | 82.7[b] | 84.6[ab] | 1.14 | 0.0326 |
| Thr | 80.3[a] | 84.1[a] | 74.9[b] | 76.3[ab] | 1.88 | 0.0164 |
| Trp | 89.0[ab] | 90.6[a] | 80.1[c] | 81.8[bc] | 1.59 | 0.0006 |
| Val | 82.6[ab] | 85.6[a] | 77.2[b] | 77.9[ab] | 1.6 | 0.0185 |
| Dispensable AA, % | | | | | | |
| Ala | 83.9[ab] | 87.2[a] | 78.4[b] | 78.8[ab] | 1.78 | 0.0123 |
| Asp | 82.2[ab] | 84.2[a] | 76.7[b] | 79.6[ab] | 1.75 | 0.0482 |
| Cys | 77.2[a] | 81.3[a] | 68.0[b] | 70.4[ab] | 2.27 | 0.0052 |
| Glu | 86.9[ab] | 89.8[a] | 81.3[b] | 85.7[ab] | 1.64 | 0.0168 |
| Gly | 91.7[ab] | 100.9[a] | 84.2[b] | 91.6[ab] | 3.76 | 0.0348 |
| Pro | 143.6 | 155.0 | 130.1 | 154.2 | 7.8 | 0.1396 |
| Ser | 85.6[ab] | 87.1[a] | 80.6[b] | 81.9[ab] | 1.61 | 0.0317 |
| Tyr | 85.2[ab] | 87.3[a] | 80.9[b] | 82.7[ab] | 1.28 | 0.0235 |
| Mean | 89.2[ab] | 92.1[a] | 83.5[b] | 87.2[ab] | 1.49 | 0.0127 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 3.11 Apparent ileal digestibility of N and AA in experimental diets for Exp. 2[1]**

| Items | 0% SBP | 10% SBP | 20% SBP | 30% SBP | SEM | Contrast[2] Linear | Quadratic |
|---|---|---|---|---|---|---|---|
| Nitrogen | 83.5 | 77.8 | 76.8 | 66.2 | 1.94 | <0.0001 | 0.1288 |
| Indispensable AA, % | | | | | | | |
| Arg | 93.1 | 89.9 | 90.8 | 86.8 | 1.30 | <0.0001 | 0.6192 |
| His | 87.9 | 82.9 | 82.6 | 77.5 | 1.48 | <0.0001 | 0.9578 |
| Ile | 88.0 | 83.0 | 83.6 | 78.3 | 0.85 | <0.0001 | 0.8904 |
| Leu | 86.6 | 81.6 | 82.7 | 78.2 | 1.24 | <0.0001 | 0.6671 |
| Lys | 88.4 | 82.5 | 82.7 | 75.9 | 1.43 | <0.0001 | 0.6315 |
| Met | 90.1 | 86.4 | 86.0 | 82.2 | 1.05 | <0.0001 | 0.9447 |
| Phe | 87.5 | 82.8 | 83.8 | 79.0 | 1.12 | <0.0001 | 0.9682 |
| Thr | 82.2 | 73.5 | 73.6 | 67.1 | 1.54 | <0.0001 | 0.3961 |
| Trp | 87.3 | 84.6 | 83.4 | 78.3 | 1.63 | <0.0001 | 0.3306 |
| Val | 83.1 | 76.4 | 76.4 | 69.9 | 1.61 | <0.0001 | 0.8799 |
| Dispensable AA, % | | | | | | | |
| Ala | 82.4 | 76.4 | 77.0 | 71.3 | 1.31 | <0.0001 | 0.9338 |
| Asp | 86.5 | 80.6 | 80.8 | 75.9 | 1.50 | <0.0001 | 0.7729 |
| Cys | 79.0 | 69.8 | 68.3 | 62.8 | 3.13 | <0.0001 | 0.4115 |
| Glu | 91.2 | 86.4 | 85.8 | 82.8 | 1.08 | <0.0001 | 0.4049 |
| Gly | 81.3 | 70.1 | 68.1 | 57.6 | 3.50 | <0.0001 | 0.9719 |
| Pro | 83.0 | 79.6 | 73.3 | 49.4 | 11.26 | 0.0016 | 0.1010 |
| Ser | 87.1 | 81.1 | 80.3 | 75.1 | 1.69 | <0.0001 | 0.8924 |
| Tyr | 88.2 | 82.0 | 82.7 | 75.5 | 0.91 | <0.0001 | 0.6131 |
| Mean | 87.4 | 82.0 | 81.2 | 74.8 | 1.61 | <0.0001 | 0.5955 |

**[1]Least square means, n = 8/treatment**

**[2]Orthogonal contrast were used to generate linear and quadratic response**

**Table 3.12 Standardized ileal digestibility of N and AA in experimental diets for Exp. 2[1]**

| Items | 0% SBP | 10% SBP | 20% SBP | 30% SBP | SEM | Contrast[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | Linear | Quadratic |
| Nitrogen | 86.8 | 79.7 | 78.8 | 68.0 | 1.56 | <0.0001 | 0.2326 |
| Indispensable AA, % | | | | | | | |
| Arg | 94.3 | 91.1 | 92.1 | 88.0 | 1.30 | <0.0001 | 0.6192 |
| His | 89.2 | 84.2 | 83.9 | 78.8 | 1.48 | <0.0001 | 0.9578 |
| Ile | 89.2 | 84.1 | 84.7 | 79.4 | 0.85 | <0.0001 | 0.8904 |
| Leu | 87.9 | 82.8 | 83.9 | 79.4 | 1.24 | <0.0001 | 0.6671 |
| Lys | 89.9 | 84.0 | 84.1 | 77.3 | 1.43 | <0.0001 | 0.6315 |
| Met | 91.1 | 87.3 | 87.0 | 83.2 | 1.05 | <0.0001 | 0.9447 |
| Phe | 88.6 | 83.9 | 84.9 | 80.1 | 1.12 | <0.0001 | 0.3961 |
| Thr | 84.7 | 76.0 | 76.1 | 69.6 | 1.54 | <0.0001 | 0.9682 |
| Trp | 88.7 | 86.1 | 84.9 | 79.8 | 1.63 | <0.0001 | 0.3306 |
| Val | 85.1 | 78.4 | 78.3 | 71.8 | 1.61 | <0.0001 | 0.8799 |
| Dispensable AA, % | | | | | | | |
| Ala | 84.9 | 79.0 | 79.5 | 73.8 | 1.31 | <0.0001 | .9338 |
| Asp | 87.7 | 81.9 | 82.0 | 77.1 | 1.50 | <0.0001 | 0.7729 |
| Cys | 81.1 | 71.9 | 70.3 | 64.8 | 3.13 | <0.0001 | 0.4115 |
| Glu | 90.9 | 87.0 | 86.4 | 83.3 | 1.27 | <0.0001 | 0.7115 |
| Gly | 87.1 | 75.9 | 73.9 | 63.4 | 3.50 | <0.0001 | 0.9719 |
| Pro | 99.6 | 96.2 | 89.9 | 66.0 | 11.26 | 0.0016 | 0.1010 |
| Ser | 89.1 | 83.1 | 82.3 | 77.1 | 1.69 | <0.0001 | 0.8912 |
| Tyr | 89.5 | 83.3 | 84.0 | 76.8 | 0.91 | <0.0001 | 0.6125 |
| Mean | 89.8 | 84.4 | 83.6 | 77.1 | 1.61 | <0.0001 | 0.5953 |

**[1]Least square means, n = 8/treatment**

**[2]Orthogonal contrast were used to generate linear and quadratic response**

**Table 3.13 Apparent ileal and total tract digestibility of N and energy in experimental diets for Exp. 1[1]**

| AID of diets | Soybean Meal | Corn Fiber | Rice Hulls | Wheat Straw | SEM | *P*-value |
|---|---|---|---|---|---|---|
| Energy | 76.2[a] | 73.8[a] | 64.7[b] | 65.8[b] | 1.48 | <0.0001 |
| Nitrogen | 70.8[a] | 74.8[a] | 47.5[b] | 64.1[a] | 4.10 | <0.0001 |
| ATTD of diets | | | | | | |
| Energy | 91.6[a] | 89.2[a] | 81.3[b] | 80.5[b] | 1.36 | <0.0001 |
| Nitrogen | 86.2 | 87.3 | 81.5 | 84.7 | 3.76 | <0.0001 |
| Difference between ATTD and AID | | | | | | |
| Energy | 16.60 | 16.10 | 19.90 | 14.60 | 2.73 | 0.2841 |
| Nitrogen | 19.0[ab] | 10.7[b] | 28.0[a] | 18.9[ab] | 4.74 | 0.0158 |
| ADH of diets | | | | | | |
| Energy | 71.5[a] | 59.2[ab] | 53.4[b] | 44.6[c] | 3.17 | <0.0001 |
| Nitrogen | 61.2[ab] | 47.4[b] | 68.5[a] | 62.4[ab] | 5.46 | 0.0498 |

**[1]Least square means, n = 8/treatment**

**[a-c]Means in a row that do not have a common superscript letter differ at $P < 0.05$**

**Table 3.14 Apparent ileal and total tract digestibility of N and energy in experimental diets for Exp. 2[1]**

| | | | | | | Contrasts[2] | |
|---|---|---|---|---|---|---|---|
| AID of diets | 0% SBP | 10% SBP | 20% SBP | 30% SBP | SEM | Linear | Quadratic |
| Energy | 83.9 | 75.8 | 73.2 | 58.5 | 1.03 | <0.0001 | 0.0002 |
| Nitrogen | 82.4 | 76.8 | 75.5 | 65.5 | 1.27 | <0.0001 | 0.0028 |
| ATTD of diets | | | | | | | |
| Energy | 95.7 | 93.4 | 92.4 | 85.9 | 0.96 | <0.0001 | 0.005 |
| Nitrogen | 93.3 | 90.0 | 87.9 | 78.2 | 1.18 | 0.0125 | 0.1056 |
| Difference between ATTD and AID | | | | | | | |
| Energy | 10.9 | 16.9 | 19.4 | 32.3 | 1.97 | <0.0001 | 0.0002 |
| Nitrogen | 9.8 | 13.7 | 12.1 | 17.4 | 1.74 | <0.0001 | 0.0028 |
| ADH of diets | | | | | | | |
| Energy | 69.80 | 71.10 | 72.50 | 68.40 | 3.21 | 0.3256 | 0.8524 |
| Nitrogen | 57.90 | 57.50 | 56.30 | 47.70 | 4.32 | 0.1562 | 0.5726 |

**[1]Least square means, n = 8/treatment**

**[2]Orthogonal contrast were used to generate linear and quadratic response**

# CHAPTER 4. SUMMARY

As the biofuel and human food industries continue to utilize the majority of nutrient-dense grains, swine nutritionists are searching for applications of alternative feed ingredients in animal agriculture. Many alternative protein sources exist for livestock nutrition, and the nutrient digestibility varies greatly among ingredients. Dietary fiber can supply valuable energy to the production and maintenance of pigs as swine are able to digest specific fibrous fraction in the hindgut via microbial fermentation. Upon fermentation of polysaccharides, microbes release energy as VFAs, which can be used as an energy source and absorbed by other bacteria or intestinal tissue. Dietary fiber can also inhibit nutrient digestibility in nonruminants, and more research is required to understand the appropriate inclusion of fiber in swine diets. Specifically, fiber supplementation that results in maximal energy gain and minimal nutrient loss must be investigated.

The results from this thesis reveal that alternative feedstuffs can provide adequate amounts of N and AA to growing pigs and the effect of fiber on decreasing energy, N, and AA digestibility is directly related to the type and source of dietary fiber. The N and AA from sunflower and canola meal are fairly digestible in growing pigs, whereas camelina and cottonseed meals appear to contain anti-nutritional factors that impede nutrient digestion. Animal and plant protein concentrates are more efficient in

supplying N and AA than oilseed meals to pigs and should be used in intensive swine production. Comparing the effects of insoluble fiber of different composition and origin shows that these factors impact the digestibility of fiber and fiber's impact on nutrient digestion. Lignin content of dietary fiber may provide an index to predicting the nutritional value of fiber. Soluble fiber can increase microbial degradation of polysaccharides in the hindgut of pigs by increasing the surface area of digesta. However, soluble fiber can also increase the viscosity of gut material and reduce nutrient digestibility by having a high capacity to bind to water. Feeding varying levels of sugar beet pulp reveal that low inclusion levels of soluble fiber can influence energy, N, and AA absorption in pigs, and increasing the supplementation of soluble fiber can surpass the capacity of microbial fermentation to utilize energy from fiber.

Fiber composition of swine diets have been shown to significantly influence nutrient digestibility. Therefore, future experiments should be conducted to determine the impact of specific types of fiber on nutrient digestibility and gastrointestinal health in pigs. Understanding that diet composition can affect the endogenous flow of amino acids, feeding high fiber, nitrogen-free diets may provide valuable insight to calculating the AA digestibility of diets supplemented with fiber. An underestimation of nutrient digestibility can occur if fiber increases endogenous losses of AA. In terms of experimental design, feeding different sources and levels of dietary fiber to pigs of various stages of production may provide more insight to determine the impact of age on fiber digestibility, resulting in understanding the potential use of fiber in the different phases of swine production. Specifically, feeding similar, high fiber diets to young,

grow-finish, and gestating pigs may provide important information. Analyzing the crude fiber, total dietary fiber, NDF, ADF, cellulose, hemicellulose, lignin, beta glucan, and pectin composition of the experimental ingredients and diets could aid in determining the factors responsible for affecting energy and nutrient digestibility observed in the present study. Such chemical analysis is labor intensive and expensive, so more efficient methods in fiber analysis need to be developed. Additionally, analyzing the viscosity ileal digesta would be helpful in understanding the water-binding capacity of insoluble and soluble fiber fractions of the ingredients tested in this study. With this study's objective of understanding alternative feed and fiber digestibility, it may prove valuable to determine the nutrient retention of such diets. Therefore, urine collection and analysis of nutrients would allow researchers to determine nutrient retention of high fiber diets.

As feeding dietary fiber results in abrasive material passing through the digestive tract, it may be beneficial to observe the impact specific fibrous fractions have on villi height and crypt depth of the small intestine and crypt depth of the large intestine. Better understanding the influence of fiber on the gut lining would then be encouraged. Measurement of crypt depth and villi height is an efficient procedure. However, this would require the cannulated pigs to be sacrificed at the end of each experiment. With cannulation being a labor-intensive and expensive procedure, harvesting tissue from the pigs may not be a very cost efficient practice. Molecular analysis of AA transporters may provide insight to understanding if dietary impacts the absorption process in the intestine. Measuring the activity of passive and active

transporters of AA should occur as the understanding of fiber digestion in swine nutrition continues to improve.

As swine nutritionists develop more efficient feeding programs, understanding the nutritional value and impact of alternative feed ingredient is essential. Determining the influence of fiber in these ingredients on total diet digestibility will enable more proficient utilization of by-products that are readily available to swine producers.